

**QUASARS, CARBON, AND SUPERNOVAE:  
EXPLORING THE DISTRIBUTION OF ELEMENTS  
IN AN EXPANDING UNIVERSE**

by

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# QUASARS, CARBON, AND SUPERNOVAE: EXPLORING THE DISTRIBUTION OF ELEMENTS IN AN EXPANDING UNIVERSE

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University of Pittsburgh, 2013

This thesis consists of three different studies with a common goal of understanding the constituents and structures of the universe.

The current understanding of galaxy formation is not complete. Cold and hot flows in galaxies play a role in the evolution and transportation of elements within halos. Ionized carbon clouds are often observed in the spectra of back-lighting quasars. I study the clustering properties of the triply ionized carbon clouds from SDSS-III data to determine the minimum mass of the host halo in which galaxy formation processes produce such clouds. Apart from enabling better understanding of these clouds, this result will help constrain galaxy formation theory and the associated feedback processes.

Standard cosmological theory produces an excess of baryonic structure compared to the observed one. Energetic quasars are often envisaged as the process which injects kinetic energy into the structures and halts the structure formation. I study the outflow in SDSS-III quasars through the observed velocities of the triply ionized carbon clouds detected in their spectra. Using more accurate modeling of the abundance of carbon clouds, I make robust conclusions about properties of outflow systems. Understanding the velocities of such outflow helps constrain the amount of energy injected in the feedback process of quasars and helps in explaining the observed baryonic structure of the Universe.

Supernovae Ia enable us to measure distances at different redshifts. Distances enable us to infer the expansion history of the Universe and measure the current accelerated expansion. The equation-of-state parameter,  $w$ , of the dark energy responsible for this acceleration, can

be determined from the expansion history. I estimate  $w$  using data from ESSENCE and other current supernova surveys and measure the effect of the important systematic uncertainties that are expected to have the largest contribution to the uncertainty in our understanding of dark energy.

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## PREFACE

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## 1.0 INTRODUCTION

This dissertation explains the background and details of my contribution to improve the understanding of the Universe and its constituent. I study constituents different epochs of the Universe, encompassing the distribution of elements during the epoch when galaxies were very actively evolving and forming stars to the acceleration of the expansion of universe at recent epochs.

The first chapter provides a brief introduction to our current understanding of the universe and the relevance of my thesis towards improving that understanding. It explains the current standard cosmology, also known as  $\Lambda$ CDM cosmology, which explains various important epochs of the evolution of the universe. The different projects of my thesis are presented in each of the chapter. In Chapter 2, I measure the special clustering strength of carbon clouds with respect to quasars to determine the host halo mass of these absorbers. In Chapter 3, I present the most detailed measurements and analysis to date of the carbon clouds from the outflow of quasars. In Chapter 4, I measure properties of dark energy using Supernovae Ia and estimate the systematic error due to the largest expected contributors. In the Appendix, I describe the enhancement to a pipeline used to detect absorption lines in quasar spectra. The enhanced absorber pipeline is used in the work described in Chapter 2 and Chapter 3.

In the standard picture of  $\Lambda$ CDM cosmology, the universe is made of three main constituents: 1. Matter; 2. Radiation; and 3. Dark Energy. The “Matter” component can be further divided as “dark matter”, which only interacts gravitationally, and ordinary matter (baryons). Fig. 1.1 shows the contributions of different components. The contributions of dark energy, dark matter, and baryons are approximately 74%, 22%, and 4% respectively, of the total energy density at the present epoch, while the contribution of radiation is neg-

ligible (Komatsu et al. 2011; Larson et al. 2011; Jarosik et al. 2011). The dark matter is approximately five times more abundant than the ordinary matter and therefore plays a central role in the formation of structures, while the ordinary material largely traces the gravitational potential defined by the dark matter. Standard cosmology also assumes that Einstein's theory of General Relativity, which has been tested quite accurately at various scales, is the guiding principle for the universe. The density of each components evolves at a different rates; because of this, at various times during the evolution of the universe, different components played the dominant role. The geometry of the universe has been measured to be very close to being flat with a high degree of accuracy (Komatsu et al. 2011; Larson et al. 2011; Jarosik et al. 2011). As such, I assume it to be flat throughout this dissertation.

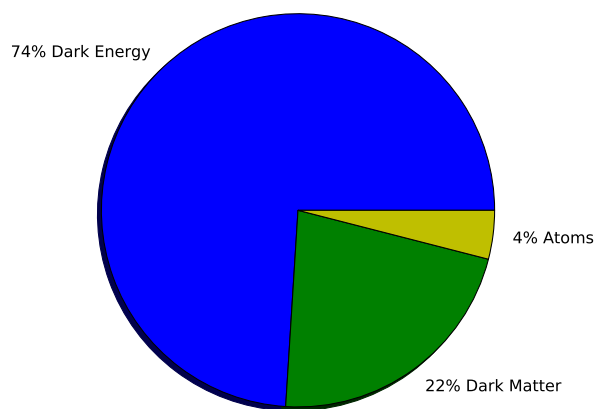


Figure 1.1 The constituents of the universe at the present epoch. The dark energy, dark matter and baryons are approximately 74%, 22% and 4% of the total energy density. The radiation is negligible at the present epoch.

## 1.1 EARLY UNIVERSE

The universe is believed to have been in a very hot and dense state at the earliest fraction of a second. The natural forces were unified. As the universe expanded, it cooled and

the natural forces started to separate. This expansion was most dramatic during a period of “inflation”, during which it increased about  $10^{50}$  times in scale (see Fig. 1.2). As the cooling process continued, the quarks and photons remained in thermal equilibrium. When the universe cooled sufficiently, the quarks combined to form stable protons and neutrons. As the cooling continued, the neutrons and protons interacted and started to fuse together to make nuclei of elements heavier than hydrogen, a process called “nucleosynthesis”. The era of nucleosynthesis created nuclei of helium and a very small amount of lithium and beryllium. These nuclei and free electrons continued to interact with photons because they are electrically charged and thus easily interact with photons. The large cross-sections of nuclei and free electrons inhibited free streaming of photons and made the universe opaque. The temperature eventually cooled enough ( $T \sim 3000$  K) for the electrons to combine with nuclei to make neutral atoms. These atoms, being neutral, did not strongly interact with photons (peak  $\lambda \sim 1\mu\text{m}$ ), allowing photons to stream freely afterwards. We observe these photons today as the Cosmic Microwave Background (CMB). This epoch is known as the “recombination” era (Fig. 1.2, Marked as “Afterglow Light Pattern”).

## 1.2 STRUCTURE FORMATION

The universe continued to expand and cool after recombination. The matter component of the universe at this point consisted of dark matter and atoms of hydrogen, helium, and traces of lithium. Due to the expansion of the universe, the CMB photons were redshifted out of the optical range. No stars or other bodies had yet formed; there was nothing hot enough to generate optical photons. Due to the lack of optical photons, this era is also known as the dark ages. The dark matter formed large scale structure by gravitating to initial regions of small overdensities. Subsequently, these overdensities grew bigger and gas clouds of hydrogen and helium fell into them. The gas clouds continued to cool through radiation and form more dense clouds. The gravitation instability in these clouds caused the gas to collapse and form the first generation of stars, also known as population III stars (see Fig. 1.2; Bromm et al. 2009; Chiappini et al. 2011). The first stars were much more massive



than stars found today. Massive stars are both short lived and very bright. Such extreme brightness caused the ionization of regions surrounding the stars, and the universe became ionized again. This epoch is also called the era of reionization ([Wyithe and Loeb 2003](#); [Bromm et al. 2009](#); [Robertson et al. 2010](#)).

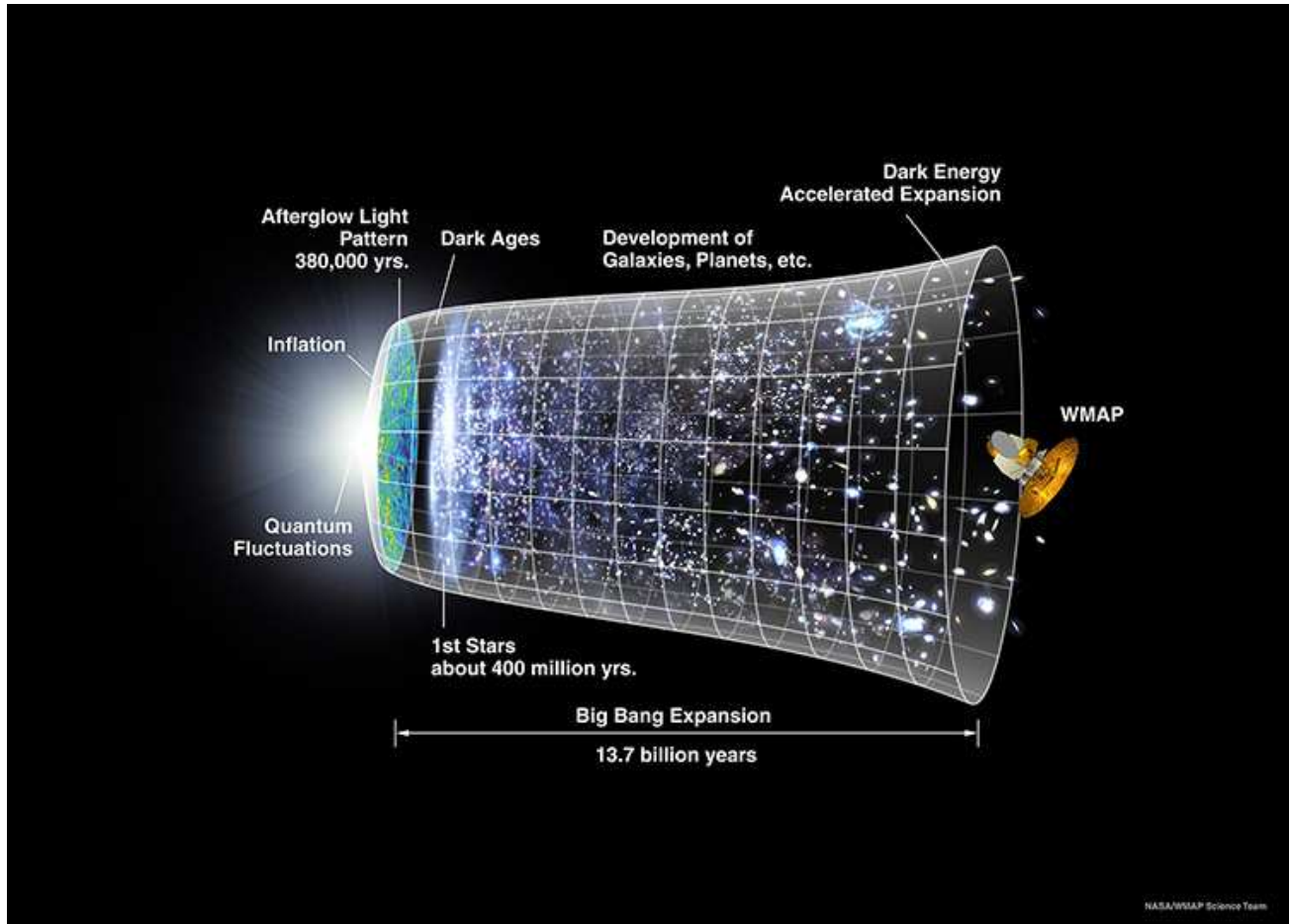


Figure 1.2 Evolution of the universe over 13.7 billion years. Important epoch of inflation, recombination, dark ages, and first star formation are shown. Credit: NASA / WMAP Science Team

Small inhomogeneities in the early universe started to grow after recombination. Dark matter gravitated towards overdensities. Fig. 1.3 shows the simulated structure of universe at large scale. The plots, from top left to bottom right, are snapshots of the universe at redshift  $z=18.3$ , 5.7, 1.4 and 0.0 from a numerical simulation called the Millennium Simulation ([Springel et al. 2005](#)). As can be seen from these plots, the structures are more evolved and show filamentary structure at smaller redshift. Fig. 1.4 shows the observed structure

of our local universe, where each point denotes a real galaxy. The filamentary structure, as predicted by the simulation, is evident in the observed data, leading to the conclusion that ordinary matter follows the dark matter potential.

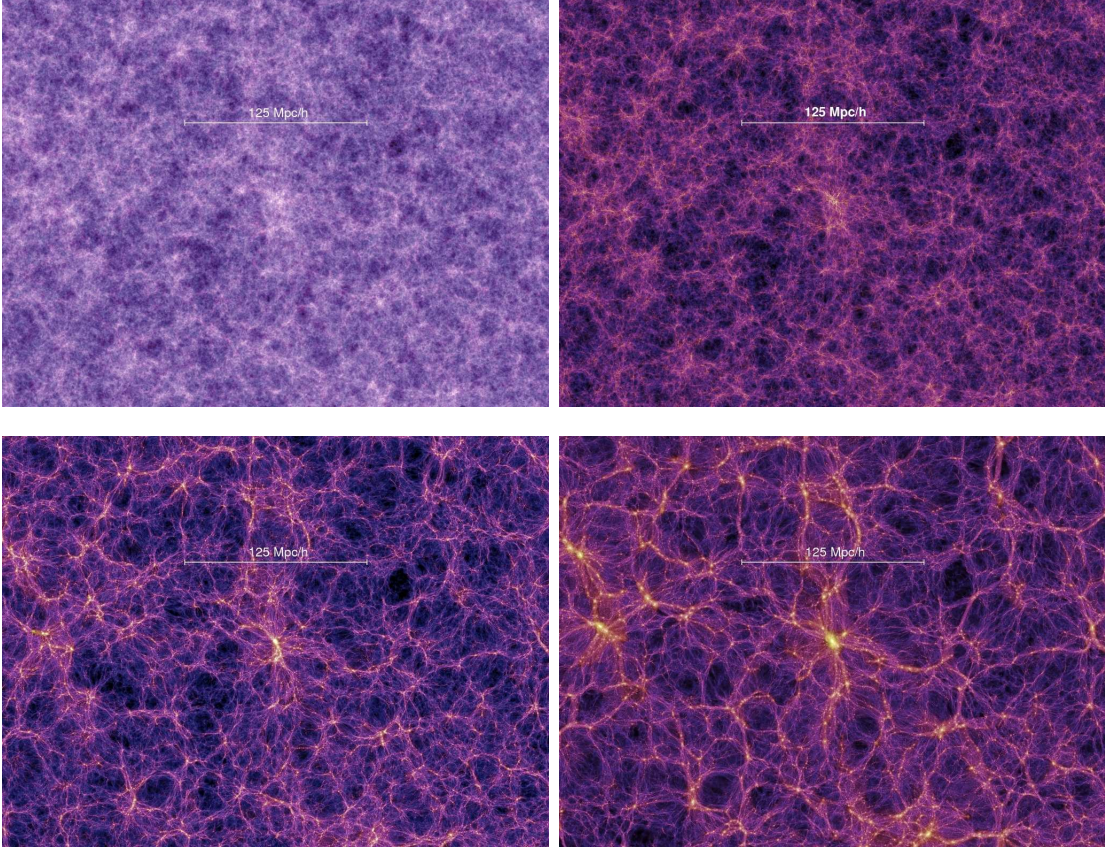


Figure 1.3 Computer simulation of large-scale structure of universe from the Millennium Simulation. From top left to bottom right the structure at redshift  $z=18.3$ ,  $5.7$ ,  $1.4$  and  $0.0$  respectively. The bar in each figure shows the scale of  $125 \text{ Mpc}/h$ . ([Springel et al. 2005](http://www.mpa-garching.mpg.de/galform/virgo/millennium), <http://www.mpa-garching.mpg.de/galform/virgo/millennium>)

The structures continued to evolve, enhancing inhomogeneity. Baryons condensed in these overdensities and began to form more complex object than stars (e.g., proto-galaxies, quasars, galaxies, galaxy clusters etc.). Quasars are known to have existed as early as redshift  $7.085$ , which is only  $0.77$  billion years after the Big Bang ([Mortlock et al. 2011](#)). Formation of baryonic structure at any time affects the formation and evolution of subsequent structure, hence understanding the structures at all epochs is important to achieve a complete understanding of evolution of universe.

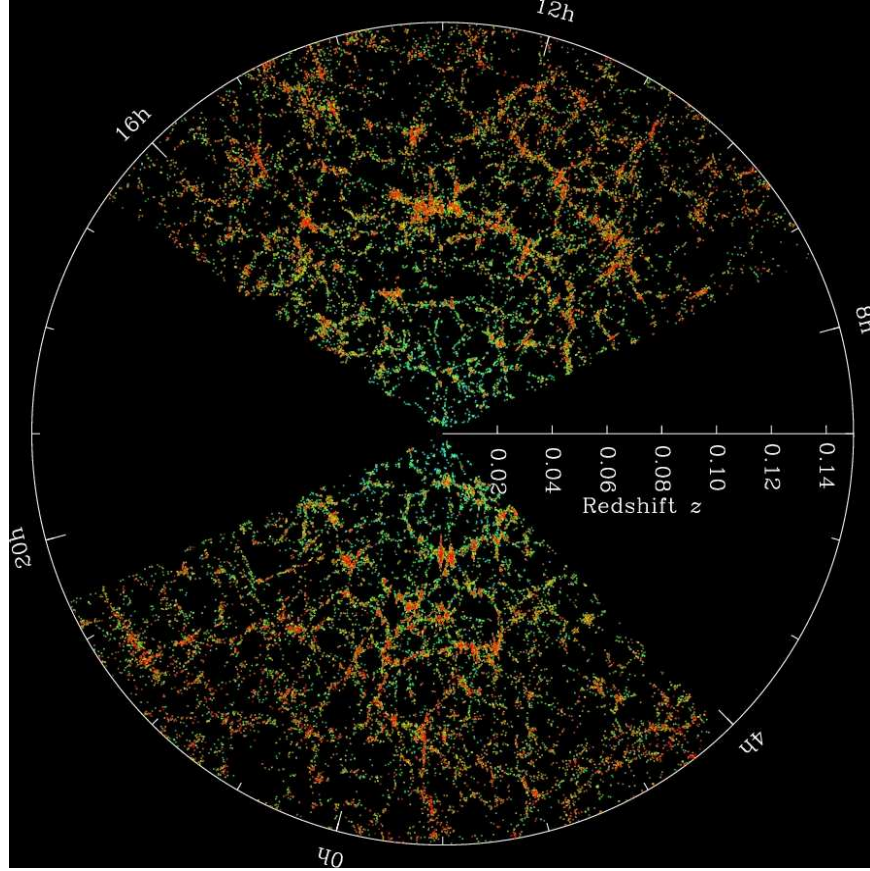


Figure 1.4 Structure of the local universe. The points are location of galaxy, the filament structures of large scale are evident from the figure. Courtesy: Michael Blanton/SDSS III

### 1.3 QUASARS

Quasars are extremely bright sources of light, exceeding trillions of times the brightness of the Sun ( $\sim 2 \times 10^{12} L_{\odot}$ ), and yet they are point-like objects on the sky, suggesting that they are much smaller than galaxies. A quasars's brightness makes it observable across the visible universe.

Quasars are believed to be powered by accretion around super massive blackholes (SMBH) at the center of galaxies ([Urry and Padovani 1995](#)). Super massive blackholes (SMBH) are black holes that are typically hundreds of millions of solar masses. The accretion disk around the SMBH feeds the black hole to cause powerful jets. The accretion disk radiates due to heat caused by gravitational potential and compression. Quasars are often a few hundred



times brighter than the galaxy in which they reside. Extreme radiation near quasars ionizes the surrounding gas. Strong winds from the quasar accretion disk blow the ionized gas out into the environment of the quasars ([Balsara and Krolik 1993](#); [Krolik and Kriss 1995](#); [Proga et al. 2000](#); [Krolik and Kriss 2001](#); [Proga and Kallman 2004](#); [Everett 2005](#)).

In this thesis, I make extensive use of quasar observations to improve the understanding of baryons in quasar systems, as well as using them as background light to understand intergalactic material in the universe. In the next few sections, I discuss the history and present understanding of these fascinating objects.

### 1.3.1 Discovery and Basic Nature of Quasars

The discovery of quasars is a result of the development of radio astronomy. The existence of cosmological sources of radio waves was established in the 1950's. The polarization of these radio waves suggested the origin to be a synchrotron processes, in which the moving electrons radiate in the presence of a magnetic field. The estimated energy output from these objects was so large that the idea of a gravitational potential from normal matter as the source of energy was soon shelved. As the resolution of radio telescopes improved, the search for the optical counterparts of these radio sources caught on. The first few identified optical counterparts looked like stars, and their redshifts were identified from optical spectra. These redshifts suggested that the distances to the systems were on a cosmological scale; the redshifts/distances enabled the estimation of the energy output of these systems. These star-like objects, being very compact objects, emitting energy that was hundreds of times the output of a galaxy, were called Quasi-Stellar Objects (QSO) or quasars.

The early definition of a quasar was summarized by [Burbidge \(1967\)](#) as follows:

- star-like object identified with a radio source
- variable light
- large ultraviolet flux of radiation
- broad emission lines in the spectra with absorption line in some cases
- large redshift

The theoretical understanding of quasars progressed with the observations in the early days. [Hoyle and Fowler \(1963\)](#) suggested that compact gravitationally collapsed objects could serve as the energy source for such energetic objects. The existence of jets in early identified quasars also suggested the existence of violent processes ([Rees 1967](#); [Blandford and Rees 1974](#)). These ideas soon led to the following picture of quasars: an accretion disk is formed around a super-massive black hole, many orders of magnitude larger than the mass of typical stars, with jets coming out perpendicular to the accretion disk. With advances in theoretical understanding of in-falling material on to a compact object (e.g., neutron star, black hole), the understanding of accretion disks a torus-like thick disk in the quasar environment was established ([Shakura and Sunyaev 1973](#); [Lynden-Bell and Pringle 1974](#)). Even though a detailed understanding of quasars is still elusive, the existence of an accretion disk and a thick torus around a super-massive blackhole (SMBH) with jets coming out from the pole is still accepted as the current basic description of quasars.

### 1.3.2 Unified Quasar structure

Since the discovery of cosmological radio sources and their optical identification, there have been many observational efforts undertaken to try to identify these non- typical objects, using various ranges in the electro-magnetic spectrum, from radio to X-ray. Various classifications of objects that are not typical stars or galaxies have come from these efforts. The objects are classified in various categories according to the properties of their spectra. Below I give a brief description of a select few.

**Seyfert Galaxies:** First identified by [Seyfert \(1943\)](#), these galaxies contain bright star-like nuclei and their spectra have broad emission lines. With identification of more such galaxies, Seyfert galaxies were further classified as type 1 and 2. The type 1 Seyfert galaxy nucleus has a strong continuum from far infrared to X-ray. The few emission lines are generally broad but some narrow emission lines can be present. The type 2 galaxy nucleus has a much weaker continuum and only contains narrow emission lines.

**Radio Galaxies:** Radio galaxies are galaxies which are identified as radio sources. Most of these galaxies have an elliptical morphology. The radio emission shows a complex

morphology for the radio emitting region. Radio galaxies are further classified according to emission line properties as Broad-Line Radio Galaxy (BLRG) and Narrow-Line Radio Galaxies (NLRG). As the name suggests BLRGs have some emission lines which are broad, while in NLRGs, all the emission lines are narrow.

**Blazars:** This family of objects shows rapid variability and features a spectrum dominated by non-thermal emission. Blazars are subdivided into BL Lac and OVV subclasses. BL Lac objects are generally strong X-ray sources. These objects do not show strong emission lines. They also demonstrate high polarization and are a strong source of radio emission. Optically violent variable (OVV) quasars show rapid variation in their optical spectrum.

These diverse classes of object, though having many peculiarities, have many underlying similarities. These similarities naturally give an opportunity to attempt a unification of these classes with a general model using only few basic parameters. While many theories that have attempted to unify a few classes have enjoyed limited success, the attempt to unify various classes is far from over. I present here the most popular unification scheme. The review article [Urry and Padovani \(1995\)](#) covers this scheme in great detail. The level of scientific verification varies for different parts of the model.

Quasars originate from matter falling in to a SMBH at the center of the galaxy. The falling gas forms an accretion disk. The viscous and turbulent processes in the accretion disk cause the gas to lose angular momentum, thus bringing it closer to the event horizon of the black hole. During this process, the accretion disk heats up and glows brightly in ultraviolet and soft X-rays. Hard X-rays are produced very near to the black hole emitted by hot electrons. The rapidly moving gas cloud in the potential of the SMBH produces strong emission lines in the optical and ultraviolet. There is a thick torus made of gas and dust aligned with the accretion disk. The torus obscures the SMBH and the associated broad-line emission gas cloud from lines of sight near the equatorial plane. Gas clouds away from the torus produce narrow emission lines. The SMBH also forms jets of energetic particles in the direction of the poles. These jets interact with the Inter-Stellar Medium (ISM) and produce radio emission. Thus in an elliptical galaxy, due to more ISM in the direction of jets, the radio sources are strong compared to the spirals. The lines of sight near the equatorial plane are blocked by the dusty torus, preventing observation of the broad emission line gas

cloud, resulting in spectra with only narrow emission lines. The above picture of the SMBH region in galaxies attempts to explain the different classes of observed spectra as differences in viewing angle, mass and spin of the SMBH, and accretion rate. Details of these processes are still not resolved.

One of the important features of the unified scheme is the outflow of the gas from the accretion disk. The origin of such outflows is not very well understood. The outflow may be accelerated by magneto-centrifugal forces, or by radiation pressure, or by pressure driven wind, depending on the different model. In the case of an outflow dominated by radiation pressure, the flow is confined to low latitudes with respect to the accretion disk plane. According to simulations (Proga et al. 2000; Proga and Kallman 2004), some transient filaments of higher density form. In the case of outflows dominated by magneto-centrifugal forces, the flow is more cylindrical (Everett 2005). In the case of outflows dominated by gas pressure, the wind is generated from the cool, dense torus, by photo-evaporation; therefore the wind does not originate deep inside the potential well, and it has a smaller outflow velocity (Balsara and Krolik 1993; Krolik and Kriss 1995, 2001).

### 1.3.3 Quasar Properties

The quasar spectrum shows broad emission lines in the ultraviolet and optical parts of the spectrum. At high redshift, the most commonly observed emission line is C IV, due to redshifting of ultraviolet features into the observable optical range. These emission lines are generated very near to the accretion disk of SMBH and an intrinsic part of quasars. Baldwin (1977) was the first to observe the anti-correlation between luminosity and the equivalent width of C IV. The effect has been confirmed by many studies (e.g., Wu et al. 2009; Richards et al. 2011) and is due to a lack of atoms in higher ionizing states, because of the lack of ionizing photons in low brightness quasars.

Quasars emit over a very broad range of the electro-magnetic spectrum and are bright in ultraviolet through X-ray. They exhibit an anti-correlation of ultraviolet luminosity and X-ray luminosity. More specifically, there is a suggested nonlinear inverse scaling of 2 keV X-ray luminosity with the ultraviolet luminosity at 2500 Å (Avni and Tananbaum 1982;

[Green et al. 1995](#); [Steffen et al. 2006](#); [Just et al. 2007](#); [Richards et al. 2011](#))

It is also well observed that the emission lines in quasar spectrum are systematically blue-shifted compared to the true redshift. The blue-shift varies for different emission lines, with a more severe blue-shift for higher ionization lines. The blue-shift also depends on the luminosity, though the luminosity dependence is much weaker in radio-loud quasars compared to radio-quiet quasars ([Richards et al. 2011](#)).

#### 1.3.4 Significance of Quasars for cosmology

Quasars are a very useful probe for enhancing our understanding of cosmology. The quasars observed at redshift  $\sim 6$  provide a wealth of information about the epoch of reionization ([Becker et al. 2001](#); [Fan et al. 2001, 2003](#); [White et al. 2003](#); [Djorgovski et al. 2006](#)). They are one of the very few tools available to us to probe this epoch.

Quasars could have a significant effect on the evolution of baryonic objects (e.g., galaxies). The highly energetic narrow jets and less energetic but broader outflows give a significant amount of energy to the surrounding ISM. Such a feedback process has been hypothesized to regulate the evolution of the galaxies ([Silk and Rees 1998](#); [Springel et al. 2005](#); [Di Matteo et al. 2005](#); [Bower et al. 2006](#)).

Quasars are also very useful in probing everything along their sight-line. The intervening objects between the quasar and us often imprint absorption features in spectra. These absorption lines (QALs) provide information about the quasar environment as well as the Inter-Galactic Medium (IGM). QALs have been used to study a broad range of subjects, ranging from quasar environments (e.g., [Foltz et al. 1988](#); [Aldcroft et al. 1994](#); [Richards 2001](#); [Ganguly et al. 2001](#); [Baker et al. 2002](#); [Vestergaard 2003](#); [Yuan and Wills 2003](#); [Richards 2006](#); [Ganguly et al. 2007](#); [Lundgren et al. 2007](#); [Misawa et al. 2007](#); [Ganguly et al. 2007](#)) to large scale clustering (for example, [Petitjean and Bergeron \(1990\)](#); [Steidel and Sargent \(1992\)](#); [Petitjean and Bergeron \(1994\)](#); [Outram et al. \(2001\)](#); [Churchill et al. \(2003\)](#); [Adelberger et al. \(2005\)](#); [Bouché et al. \(2006\)](#); [Scannapieco et al. \(2006\)](#); [Wild et al. \(2008\)](#); [Tytler et al. \(2009\)](#) [Lundgren et al. \(2009\)](#); [Crighton et al. \(2011\)](#))



### 1.3.5 Understanding the origin of quasar absorption systems

The star formation rate peaked between redshift  $\simeq 2$  and  $\simeq 3$  and decreased by an order of magnitude by the present day (Hopkins and Beacom 2006). Since stars are the only source for elements heavier than lithium, the QALs at this redshift range are a great tracer of star formation and galaxy evolution. One of the most easily detectable absorber systems at this redshift is triply ionized carbon (C IV). The C IV transition at wavelength  $1549\text{\AA}$  is in the ultraviolet range ( $100\text{--}4000\text{\AA}$ ) of the spectrum, but since the photons are redshifted, they reach us in the optical part of the spectrum, if they originate at a redshift greater than 1.5. We can understand the origin of these C IV systems by measuring their clustering strength. For example, in the simple model where C IV systems originate from population III stars, C IV systems would be more homogeneously distributed and their clustering strength would be similar to the strength of the dark matter itself. However, if the C IV gas originated in star-forming galaxies and was expelled by supernova blast waves into the intergalactic medium, we would expect the C IV systems to have a higher clustering strength matching that of star-forming galaxies. Alternatively, if the C IV systems result from quasars and are expelled by outflows, we would expect the C IV systems to have a strong clustering strength similar to quasars. Our understanding of structure formation by dark matter enables us to use the clustering strength of dark matter halos to find the mass of the halo at any epoch. Since C IV (like any baryon) traces the dark matter, the clustering strength measurement gives the mass of the host halos of these systems.

Measuring clustering strength requires an accurate understanding of observational constraints and the selection effects due to these constraints. The complexity of constraints of quasar observations along with extracting the absorber's information from the spectra makes it difficult to directly measure the clustering strength of C IV. However, ever-useful quasars help us determine the clustering strength indirectly by measuring the clustering strength of C IV with respect to a quasar. We have numerous observations of quasars in the same volume as the C IV absorbers, and the understanding of their population is quite accurate. In Chapter 2, I determine the clustering strength of C IV absorbers by measuring their relative clustering with quasars.

### 1.3.6 Understanding Quasars using absorption lines

Many quasar spectra demonstrate various QALs, (e.g., Mg II, C IV, Ly- $\alpha$ , Ly- $\beta$ , Si IV, Fe II). These are generally subdivided as Broad Absorption Line (BAL) or Narrow Absorption Line (NAL). These absorption features are an excellent way to probe the environment of the quasar, as some physically reside in this environment (Weymann et al. 1979; Yuan and Wills 2003; Richards 2006; Ganguly et al. 2007; Lundgren et al. 2007; Foltz et al. 1988; Aldcroft et al. 1994; Ganguly et al. 2001; Baker et al. 2002; Vestergaard 2003; Richards 2001; Misawa et al. 2007; Ganguly et al. 2007). C IV gas clouds are frequently observed in the quasar spectrum with redshift similar to that of the quasar, making them the obvious candidate to probe the quasar environment. In Chapter 3 we study the quasar environment using the C IV absorbers associated with quasars. However, all C IV clouds observed in the quasar spectrum are not due to their local environment. The intervening space also makes a significant contribution, but because we only observe velocity not actual distance, it is hard to classify them according to their origin. We can improve our study if we try to account for C IV clouds statistically rather than individually. In Chapter 3, we estimate the intervening component and use it to estimate the population and properties of C IV clouds in quasar environments.

At redshift  $\simeq 1$ , the dark energy started to have non-negligible influence on the rate of expansion of the universe. By redshift  $\simeq 0.3$  the dark energy became the dominant component of energy density and improving our understanding of dark energy has assumed foremost importance in understanding our present-day universe.

## 1.4 SUPERNOVA

Supernova Ia cosmology burst onto the center stage of cosmology by discovering acceleration of the expansion of universe (Riess et al. 1998; Perlmutter et al. 1999). The acceleration is attributed to a component of the universe that has a negative pressure, which is called Dark Energy. The negative pressure leads to the acceleration of expansion of the universe, as

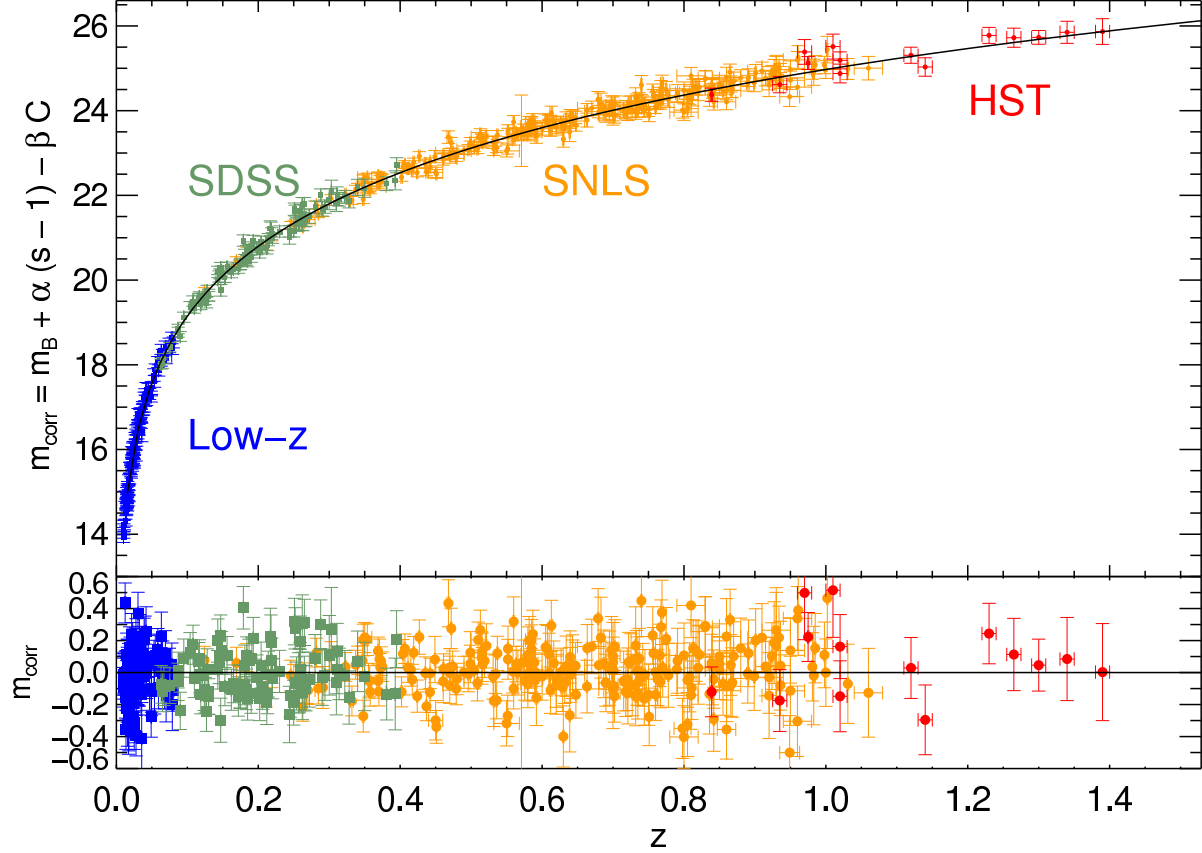


Figure 1.5 The plot of apparent magnitude with redshift from the supernova data. The black line is the best fit cosmology parameter for the data. (From: [Conley et al. \(2011\)](#))

opposed to other forms of energy which lead to deceleration. At present, 74% of the total energy in the universe is in the form of dark energy, as shown in fig. 1.1. The discovery of dark energy was made using Type Ia supernovae as the standard candles ([Riess et al. 1998](#); [Perlmutter et al. 1999](#)). Standard candles are light sources for which the brightness is always the same. By measuring the apparent brightness of these sources, the distance to the source can be estimated. The estimation of distances from many supernovae at different redshifts traces the expansion at various epochs and constrains the nature of dark energy. Figure 1.5 shows a plot of distance and redshift in the most recent supernova analysis of [Conley et al. \(2011\)](#).

Since the discovery of dark energy, the next challenge has been to estimate the equation of state parameter of dark energy,  $w$ , describing the relation of the pressure of dark energy

to the energy density of dark energy. The next generation of surveys, such as ESSENCE (Miknaitis et al. 2007), aimed to measure the  $w$  of dark energy. Due to the increased number of observed supernovae, the statistical uncertainty in supernova analysis has decreased. However, there remain many systematic uncertainties due to various assumptions and unknowns. The systematic uncertainties of supernova analyses now exceed the statistical uncertainties. It is now imperative to understand the systematic uncertainties so that further progress can be made.

In Chapter 4, I estimate  $w$  and the systematic uncertainty carefully for the ESSENCE supernova survey. In next few sections, I describe the history and current understanding of supernova Ia, which have changed our understanding of the universe in a very significant way in the last decade.

#### 1.4.1 Supernovae Ia and Properties

Supernovae are a transient event following the explosion of a star. At their peak brightness, they can match the brightness of the galaxy in which they reside. Since they are very bright, supernovae can be seen to large distances and probe the universe in the distant past. Their standard brightness can be used as a tool to measure their distances. They are also factories for making and distributing new elements, making them important for galaxy evolution and composition in the universe.

Supernovae have been centers of curiosity since the 20th century. In early observations, they were described as “novae” (new stars). In a famous debate between Shapley and Curtis, they argued about the nature of these “novae”. Shapley (1921) argued them to be novae and thus nearby objects. Curtis (1921) argued them to be in separate galaxies and to be inherently different objects compared to novae. The debate has been detailed in Trimble (1995). Using the locally observed properties of Cepheid variables-the period of oscillation in luminosity correlates with luminosity-Hubble deduced the distance of nearby galaxies (Hubble 1925). Hubble’s famous plot of distance vs redshift of nearby galaxies established the view of the expanding universe; such plots are now are called “Hubble diagrams”. This firmly established the extra galactic origin of these “novae”, resolving the debate.

Baade and Zwicky (1934) were the first to use the name “supernovae” for these extra bright “novae”, and were also the first to try to explain supernovae physically, by speculating that they are collapsing neutron stars. Baade (1938) was the first to highlight the uniformity of brightness in the supernova data, which made them appropriate to be used as “standard candles”. The need for classification arose when Minkowski (1941) found a spectrum of a supernova that was very different than previously observed. The supernovae from Baade (1938) had not shown any hydrogen in their spectra. They were called Type I supernovae (SN I), while the new supernova was classified as Type II. The first attempt to make a Hubble diagram using 19 supernovae was made by Kowal (1968).

Pskovskii (1968) noticed the presence of broad and deep absorption observed at about 6150Å, due to Si II at the maximum brightness, in many SN I. Supernova classification evolved with better spectra and further understanding of noise. Supernovae Type Ia (SN Ia) are currently described as supernovae which do not show any sign of Hydrogen or Helium but show a distinctive SiII absorption feature at peak brightness. SNe Ia are now understood to be thermo-nuclear reactions during which the white dwarf is totally disintegrated by the energy. All other supernovae are core-collapse, where the central region of an evolved star is converted to a neutron star or black hole due to pressure, and the outer layers are blown away due to shock.

With the advent of CCDs and more accurate measurement of light from SN Ia, it became clear that SN Ia had substantial variation in luminosity. The brighter SNIa’s are about three times brighter than the dimmer ones. Phillips (1993) demonstrated the correlation between the luminosity and the rate of rise and fall of luminosity (light curve) of the SN Ia, also referred to as the brighter-slower relationship: brighter SN Ia rise and fall in luminosity slower. It was observed for SNe Ia that the higher the luminosity, the shallower the slope of the light curve tends to be. The correction for this correlation significantly reduced the scatter of SN Ia on the Hubble plot. Figure 1.6 shows the effect of the correction of this correlation. The discovery pointed to a need to find more very well observed SN Ia at various epoch, in the local universe, so that more properties could be found to improve the standardness of SN Ia as standard candles.

Along with improvements in making SN Ia better standard candles, there were attempts

to verify the distance estimation of SN Ia independently. [Sandage et al. \(1992\)](#); [Saha et al. \(1995\)](#) used HST images to identify Cepheid variables in type Ia host galaxies. These studies established the supernova Ia absolute magnitude at  $M_V = -19.52 \pm 0.07$  mag and  $M_B = -19.48 \pm 0.07$  mag.

Because SN Ia suffer from extinction due to dust, the distance measurement is difficult. A significant improvement in measuring dust extinction was achieved when [Lira \(1995\)](#) first noticed that all SN Ia reach a common color after 30-90 days of maximum brightness, irrespective of their luminosity. Due to improvement in the dust extinction measurement, allowing a more precise measurement of the color of supernova, [Riess et al. \(1996\)](#) noticed the color of SN Ia correlates to luminosity, which is often referred to as the “brighter-bluer” relation where the brighter SN Ia tend to be bluer in color.

Significant improvement in the technology of making telescopes and computational power led to further improvement. [Riess et al. \(1998\)](#) and [Perlmutter et al. \(1999\)](#) made the breakthrough discovery about the accelerating universe using SN Ia as standard candles, a discovery that made SNe Ia central to modern cosmology.

#### 1.4.2 Progenitors of Supernova Ia

Improved knowledge of the SN Ia progenitor would be immensely useful for SN Ia cosmology. Understanding the progenitor systems could lead to significant improvement in understanding the evolution of various systematics with redshift and possibly their correlation with each other. It could also give guidance to suggestions of physical parameters which might make SNe Ia better standard candles. Even though the importance of SN Ia to cosmology can not be overstated, the basic understanding of its progenitor still eludes us.

SN Ia’s are thought to be thermo-nuclear explosions of a carbon-oxygen white dwarf, which are at, or close to, the Chandrasekhar limit of  $1.4 M_\odot$  ([Hoyle and Fowler 1960](#)).

One widely accepted progenitor is a carbon-oxygen white dwarf that grows in mass through accretion from a non-degenerate stellar companion (i.e., main sequence star, subgiant star, helium star, red giant star; [Whelan and Iben 1973](#)). The accreted matter increases the pressure in the white dwarf above the limit that can be supported by the degeneracy pressure

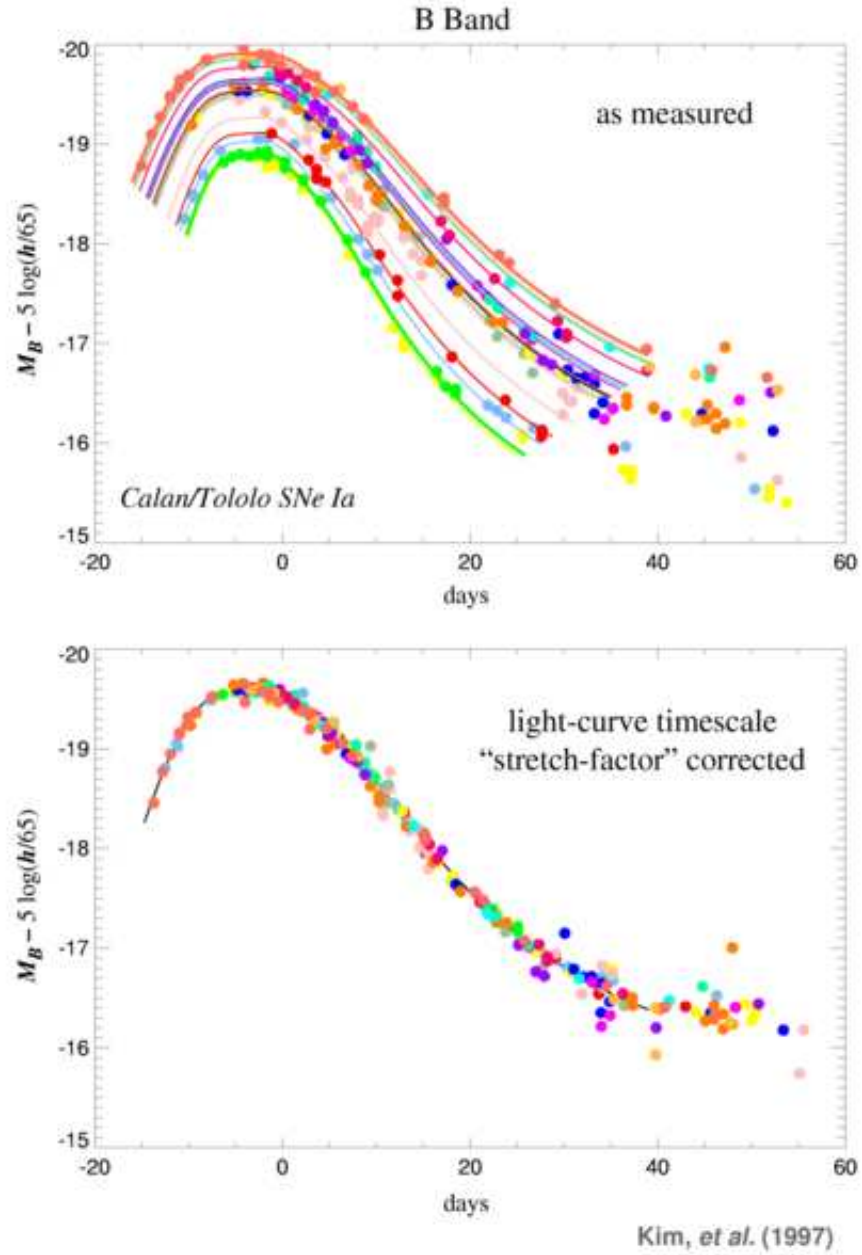


Figure 1.6 Top panel shows the different SN Ia light curves. The vertical axis is brightness and horizontal axis is time in the rest frame of SN Ia, in reference to time of maximum brightness. The bottom panel show the same light curves, taking into account the correlation between brightness and shape. This figure demonstrates that the scatter in luminosity of SN Ia is reduced significantly once the correlation is taken into account (Coursey: [Kim et al. 1997](#)).

of electrons. At this point, the nuclear burning starts and within seconds completely destroys the star. A large fraction of the star burns completely to  $\text{Ni}^{56}$ . The radioactive decay of  $\text{Ni}^{56}$  powers the light curve that we observe (Colgate and McKee 1969). Figure 1.7 (a & b) shows a cartoon picture of this progenitor model, which is also known as *Single Degenerate*.

Another model of the progenitor involves two white dwarfs merging after losing energy and angular momentum to gravitational waves (Figure 1.7 (c)). Such a merger may lead to an object more massive than the Chandrasekhar limit, which can ignite and explode. Alternatively, the process of merging might disintegrate the smaller white dwarf and may lead a super-Chandrasekhar limit white dwarf (Iben and Tutukov 1984; Webbink 1984). Since these models involve two degenerate objects, they are called *Double Degenerate*.

Both of the models were suggested many decades ago but even today there is no clear preference for any model. There is, in fact, much observational evidence against each model (e.g., Maoz and Mannucci 2011, and references therein). The observed rate of SN Ia is an example. The current SN Ia rate is considered, by some, bimodal, with one *prompt* component which is proportional to star formation rate and a *delayed* component which is proportional to total stellar mass of the galaxy (Mannucci et al. 2005; Scannapieco and Bildsten 2005). The single degenerate model fails to explain the existence of the delayed component, but the double degenerate model does not explain the prompt component well. Both models under-predict the observed SN Ia rate. Both models can only explain the SN Ia in a narrow range of some physical parameters of the model.

It is also possible that both systems result in SN Ia. The possible consequence of multiple channels of progenitor is more diversity in the supernova brightness, which would reduce their standardness. As we can see in the double degenerate case, the combined mass after a merger can exceed the Chandrasekhar mass limit, making these supernovae brighter than others. The multiple channel also brings a complicated redshift dependence to the supernova brightness. We know that in the early universe the star formation rate was much higher than it is currently. This asymmetry in star formation rate could make the supernovae at higher redshift systematically more fainter than the local ones, as they would have a higher proportion of single degenerate progenitors. To make the dependence more complicated, the brightness of supernovae is also believed to dependent on the metallicity of the progenitor in



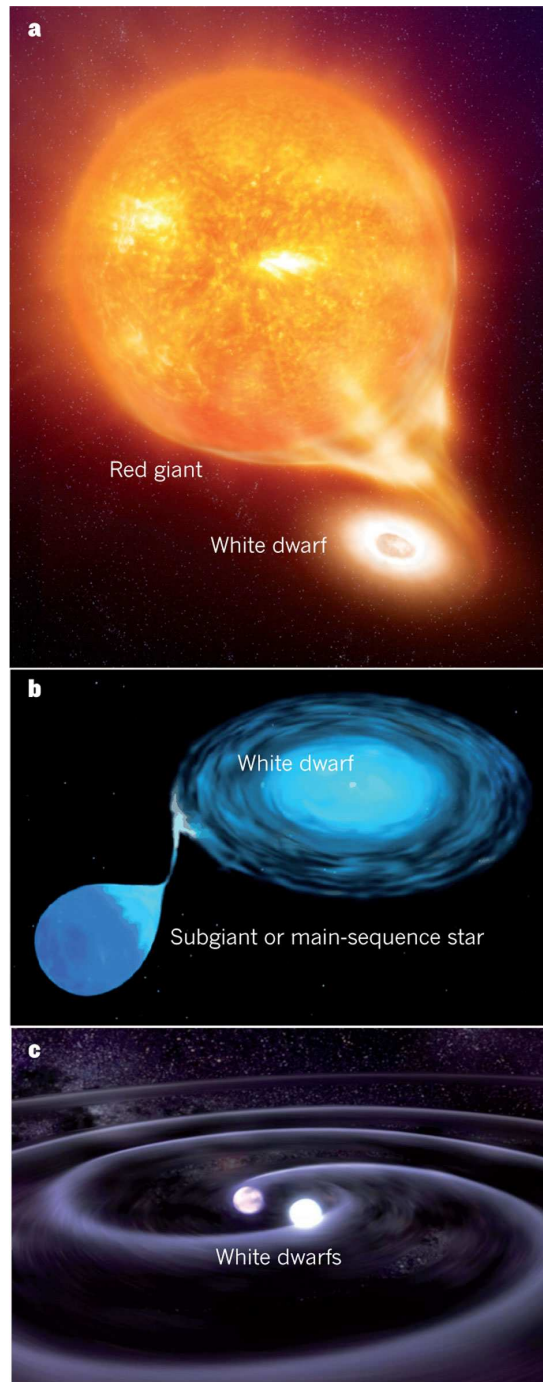


Figure 1.7 The figure is a cartoon describing the single and double degenerate progenitor of SN Ia. A white dwarf in binary system with Red Giant (a), Subgiant (b), white dwarf (c) as possible progenitor systems (Courtesy: [Hamuy 2011](#)).

the single degenerate case. Lower metallicity may make supernovae less bright ([Timmes et al. 2003](#); [Sullivan et al. 2010](#); [Konishi et al. 2011](#)). At higher redshift the metallicities are lower, and because of this, these supernovae would be fainter than more recent ones. The supernovae from double degenerate systems have a large delay time and are thus less affected by metallicity variations as a population. As we can see, our lack of knowledge of a progenitor limits our ability to use the SNe Ia as standard candles.

Even though the mystery of a SN Ia progenitor is far from being solved, the empirical standardness can still be used to provide estimates on the cosmological parameters.

## 2.0 C IV ABSORBER-QUASAR CROSS CORRELATION

The Work presented in this chapter was submitted to the *Astrophysical Journal* in May 2012. In this chapter, I study the clustering of C IV absorbers with respect to quasars. Such clustering estimates can shed light on many important questions (i.e., the origin of absorbers, feedback processes in galaxies and star formation). In §2.1, I explain the basics of absorption system detection and their properties. The estimation of clustering is contingent upon our understanding of large scale clustering of dark matter. In §2.2, I give a short background of large scale clustering theory. I explain the importance and advantages of my measurement in §2.3 in the context of cosmology, as well as the astrophysics of the host galaxies of the C IV absorbers. In §2.4, I explain the source of data for absorbers, quasars, and the random comparison catalog. I explore different correlation function estimators in §2.5 and justify my choice of the correlation estimator. In §2.6, I present the main results of this study and compare them to previous studies. In §2.7, I estimate the contribution of various systematic errors that could affect this result. In the last section of this chapter, §2.8, I summarize the main findings of my study and suggest future studies that could improve my result.

### 2.1 ABSORPTION SYSTEMS

Quasars are highly luminous objects that are believed to be super-massive black holes (Salpeter 1964; Lynden-Bell 1969) accreting material. Being very luminous, they can be seen at large distances; therefore, they are ideal for the study of large scale clustering at early cosmic times. Quasars are also very useful for probing the space along the lines of sight to the quasar. Intervening material imprints various absorption at different redshifts in the spec-

trum of a single quasar. Quasar absorption lines are currently thought to be from two sources: (1) intrinsic gas in the host galaxy of the quasar and (2) intervening gas in the galaxy along the line of sight to the quasar (e.g., [Lynds 1971](#); [Bergeron 1986](#); [Sargent et al. 1988](#); [Steidel and Sargent 1992](#); [Steidel et al. 1994](#); [Petitjean et al. 1994](#)).

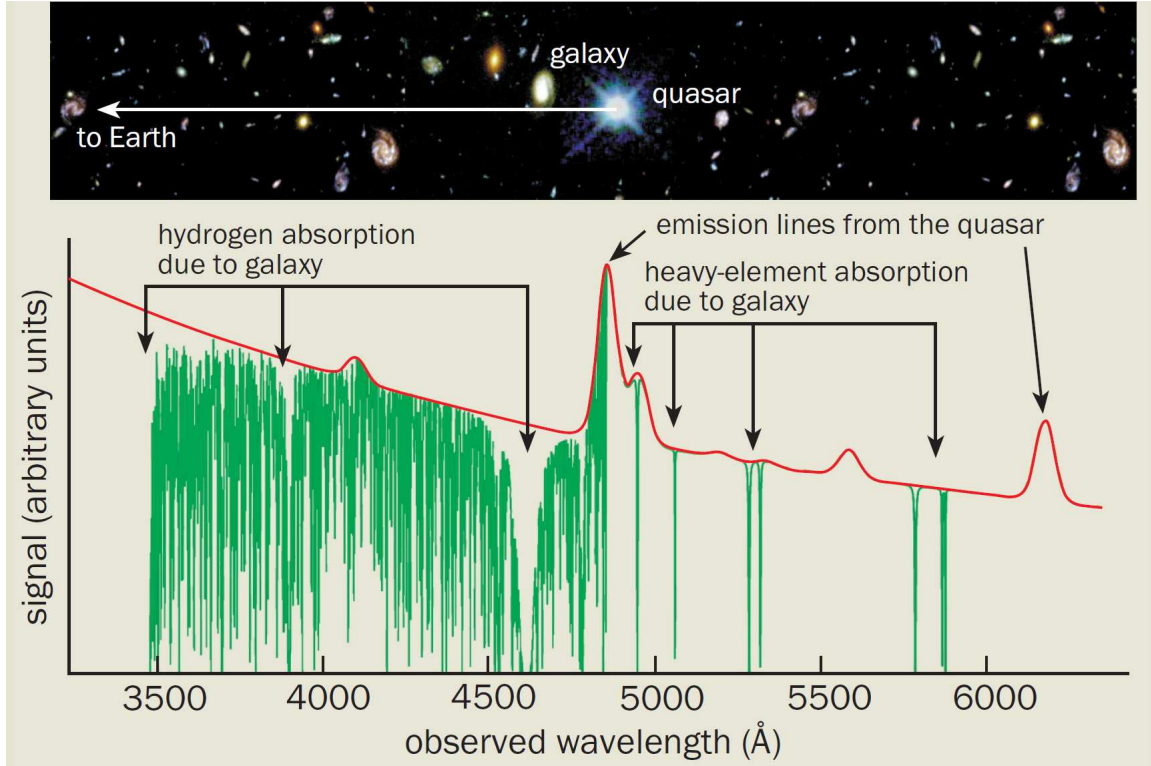


Figure 2.1 A cartoon picture of the quasar intrinsic spectrum is shown as the red line. The green line is the spectrum we observe, which has flux absorbed by material in between us and the quasar. The absorption lines identify the redshift and element causing absorption from the spectrum. Courtesy: John Webb

We describe the absorption feature in the spectrum using a measure known as “equivalent width”. The equivalent width is defined as the area enclosed by the absorption feature after normalizing the spectrum by the continuum. Fig. 2.2 illustrates the definition of equivalent width. The absorption profile at the left has the same area as the shaded region of width  $b$  at the right. The value of  $b$  is the equivalent width of the absorption profile. The equivalent width is widely used in the study of QALs, as it is a better indicator of the physical properties of the originating system than other spectral features, such as depth.

C IV is a commonly observed QAL system in quasars. The rest-frame wavelength of the

UV CIV doublet transition is (1548Å, 1550Å), which makes it easily observable in the optical region at redshift  $z > 1.5$ . The C IV transition being a doublet makes the identification of such systems more robust.

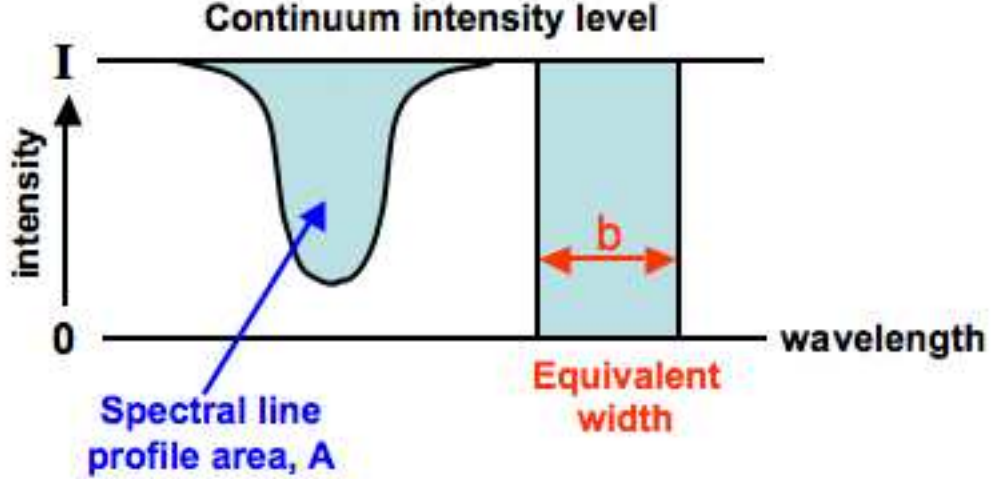


Figure 2.2 Illustration of the definition of equivalent width. The shaded areas are equal in size. The value of  $b$  is the equivalent width measurement for the absorption feature shown on the left side. Courtesy: COSMOS - The SAO Encyclopedia of Astronomy

## 2.2 LARGE SCALE CLUSTERING

The theory of large scale clustering is developed assuming a smooth distribution of matter in the early universe and small perturbations on top of that. In the limit of small perturbations, the growth of structures can be calculated. The equations are usually written in terms of the overdensity,  $\delta$ , which is defined as

$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}} \quad (2.1)$$

where  $\bar{\rho}$  is average density of the universe and  $\rho(\vec{x})$  is the density of the universe at location  $\vec{x}$ . In Fourier space, different modes of overdensity evolve independently of each other. The overdensity in Fourier space can be written as

$$\delta(k, t) = \frac{D(t)}{D(t')} T(k, t, t') \delta(k, t') \quad (2.2)$$

where  $D(t)$  is the growth function (Lacey and Cole 1993; Carroll et al. 1992; Bildhauer et al. 1992), which is independent of scale, and  $t$  and  $t'$  are different epochs.  $T(k, t, t')$  is called the transfer function (Eisenstein and Hu 1999) and governs the evolution of overdensity of different modes. The power spectrum, which is defined as the square of the amplitude (thus the power) of a given mode, can be expressed as follows.

$$P(k) \equiv \langle |\delta(k)|^2 \rangle \quad (2.3)$$

In terms of the power spectrum, the evolution of structure can be written as

$$P(k, t) = \left( \frac{D(t)}{D(t')} \right)^2 T^2(k) P(k, t'). \quad (2.4)$$

This enables us to calculate the power spectrum at any epoch, if we know the power spectrum at any earlier epoch. The power spectrum at early epochs is well observed by studying the CMB when the overdensities were small. Using the growth function and the transfer function, we can estimate the power spectrum at any epoch quite precisely. This power spectrum is often called the linear power spectrum as it holds in the approximation of small overdensities where the original equation governing the evolution becomes a linear differential equation. This power spectrum holds for dark matter, as dark matter interacts only through gravitation and is, therefore, easier to calculate. Since the dark matter density is much higher than the baryon density, the baryons follow the dark matter potential. At small real distances the overdensity is not proportionally small, but averaged over large distances, the overdensity is still extremely small and the above formalism works very well.

The overdensity of condensed baryons, like galaxies and quasars, are also small at large scales, so it can be written for any species,  $x$ , as (Efstathiou et al. 1988; Cole and Kaiser 1989; Mo and White 1996; Sheth and Tormen 1999)

$$\delta_x = b_x \delta_{\text{dm}} \quad (2.5)$$

where  $b_x$  is the bias of  $x$ . Now the power spectrum of two species  $x$  and  $y$  can be written as

$$P_{x-y}(k, z) = b_x b_y P^{\text{lin}}(k, z). \quad (2.6)$$

Since all our measurements are in real space, the above equation can be rewritten in real space by using the inverse transformation as defined below.

$$\xi(r, z) = \frac{1}{2\pi^2} \int k^3 P(k, z) \frac{\sin(kr)}{kr} d \ln k \quad (2.7)$$

The cross correlation of species  $x$  and  $y$  can then be written as below.

$$\xi_{x-y}(k, z) = b_x b_y \xi_{\text{dm}} \quad (2.8)$$

Since  $\xi_{\text{dm}}$  can be calculated using basic physics, any observation of the cross-correlation of species  $x$  and  $y$  leads to the determination of  $b_x b_y$ .

## 2.3 MOTIVATION

The origin of intergalactic QALs is not well understood. The metal lines provide information about the structure formation process. They could be produced, for example, by (1) isolated initial generation of stars (population III); (2) gas ejected into the inter-galactic medium from proto-galaxies in merger processes ([Gnedin 1998](#)); (3) gas ejected from star-forming processes within galaxies transported to large distances by galactic superwinds ([Voit 1996](#); [Heckman et al. 2000](#); [Pettini et al. 2001, 2002](#)) or jets from active galactic nuclei (AGN) ([Bahcall and Spitzer 1969](#); [Mo and Miralda-Escudé 1996](#); [Maller and Bullock 2004](#); [Chelouche et al. 2008](#)); (4) processes in the cold gas in dark matter halos ([Bahcall and Spitzer 1969](#); [Mo and Miralda-Escudé 1996](#); [Maller and Bullock 2004](#); [Chelouche et al. 2008](#)) around star-forming galaxies—the subsequent growth of large-scale structure would then make their distribution more cuspy.

One way to differentiate between these various scenarios of metal-enrichment of the intergalactic medium is to measure the clustering strength of the QAL systems ([Adelberger et al. 2005](#)). For example, in the simple model where QAL systems originate from population III stars, QAL systems would be more homogeneously distributed and their correlation function would be similar to the correlation function of the dark matter itself. However, if the QAL gas originated in star-forming galaxies and was expelled by supernova blast waves into the

intergalactic medium, we would expect the QALs to have a more biased correlation function matching that of star-forming galaxies. Equivalently, we would expect the QAL systems to reside in the same dark matter halos in which the star-forming galaxies reside. Alternatively, if the QAL systems are from quasars and expelled by outflows, we would expect the QALs to have a strongly biased correlation function similar to quasars. In other words, the QALs would reside in the same dark matter halos as quasars. The measurement of the QAL correlation function thus enables us to relate the QAL systems to the mass of the halos in which they reside.

The correlation strength of intervening QALs can also be used to better estimate the fraction of QALs that are due to the quasar environment, and do not follow the clustering properties exhibited by other QALs. In this document, we refer to all such QALs as “intrinsic,” making no distinction between systems that are sometimes more specifically referred to as “intrinsic” or “associated.” Our definition of “intrinsic” QALs thus includes those with high outward velocity with respect to quasars that overlap in redshift space with the intergalactic QALs. Understanding the correlation of the intergalactic QALs will allow for more accurate measurements of the spatial and velocity distribution of the intrinsic QALs in the future, and in turn, will help constrain the astrophysics of quasars and their host galaxies.

There have been many investigations of the clustering properties of various QALs. Because most spectra are taken in optical observer-frame wavelengths, different species of QALs have usually been studied in different redshift ranges according to their rest-frame wavelength and uniqueness of identification. Mg II ( $\lambda = 2796\text{\AA}, 2803\text{\AA}$ ) and C IV ( $\lambda = 1548\text{\AA}, 1550\text{\AA}$ ) are the two most-studied species because their prominent absorption double lines make them easy to identify. Previous works have studied Mg II systems in a redshift range of  $0.2 < z < 2$  (Petitjean and Bergeron 1990; Steidel and Sargent 1992; Churchill et al. 2003; Bouché et al. 2006; Lundgren et al. 2009). With C IV QALs we can reach the higher redshift range of  $1.5 < z < 4$ .

A number of efforts have been made to determine the C IV clustering strength, using various methods (Petitjean and Bergeron 1994; Outram et al. 2001; Adelberger et al. 2005; Scannapieco et al. 2006; Wild et al. 2008; Tytler et al. 2009; Crighton et al. 2011). A few studies have measured the auto-correlation function for C IV and other absorbers (e.g.,



Scannapieco et al. 2006). The cross-correlation of C IV absorbers with quasars or galaxies has been explored by (Outram et al. 2001; Wild et al. 2008; Tytler et al. 2009; Crighton et al. 2011). Adelberger et al. (2005) found that the cross-correlation function for C IV absorption systems and galaxies, based on  $\sim 1000$  absorbers, is similar to the correlation function of star-forming galaxies. All of these studies, however, are based upon a small number of quasars and C IV absorbers and lack the power to statistically probe the overall structure of a large volume of the Universe. Therefore, they only constrain clustering strength with relatively low precision.

New surveys with more uniform, accurate, and extensive data currently allow for a more precise QAL clustering analysis. The SDSS-III Baryonic Oscillation Spectroscopic Survey (BOSS Eisenstein et al. 2011a) provides an excellent data set for such analysis. Data Release 9 (DR9) contains high-quality spectra of  $\sim 61,000$  quasars at  $z > 2.1$  (Pâris 2012); this data set provides almost an order-of-magnitude increase in the number of QALs over previous C IV studies.

The ideal way to measure the clustering of C IV absorbers would be to perform an auto-correlation study of C IV absorbers. However, determining the uniformity and completeness of the back-lighting quasar sample together with the line-of-sight completeness of detecting C IV absorbers in quasar spectra is a significantly challenging project that requires future work. The BOSS quasar sample specifically targets quasars in the redshift range of  $z > 2.2$  (Ross et al. 2012); thus there is a good overlap between the space of C IV absorbers ( $1.5 < z < 4$ ) and the target redshift range of the BOSS quasar sample.

In this chapter, I calculate the two-point cross-correlation between the BOSS C IV absorbers and the BOSS quasars, which have a well-understood selection function (White et al. 2012), to provide a better estimate of clustering of the C IV absorbers. Because both our sample C IV absorbers and quasars are from spectroscopic data, the redshifts of each sample are known quite accurately. Therefore, here I undertake a 3-D correlation study to extract the most information from our data set.

Throughout this work, I assume a flat  $\Lambda$ CDM cosmology of  $\Omega_\Lambda=0.74$ ,  $\Omega_M=0.26$ ,  $w = -1$ , and  $h = 0.72$ .

## 2.4 DATA

### 2.4.1 BOSS

BOSS is an ongoing survey with the goal of determining the expansion history of the Universe by measuring the baryon acoustic oscillation feature using luminous galaxies at  $z \sim 0.7$  and the Lyman- $\alpha$  forest traced by quasars (Cole et al. 2005; Eisenstein et al. 2005; McDonald et al. 2006; Eisenstein et al. 2011a). The survey plans to obtain spectra for 1.5 million massive galaxies in order to measure the distance-redshift relation  $d_A(z)$  and the Hubble parameter  $H(z)$  with percent-level precision out to  $z = 0.7$ , using techniques that led to the first detection of the BAO feature (Cole et al. 2005; Eisenstein et al. 2005); the first BOSS results are given in Mehta et al. (2012); Padmanabhan et al. (2012); Xu et al. (2012). BOSS is also extending a new method of BAO measurement using the Lyman- $\alpha$  forest of 150,000 distant quasars at  $z \simeq 2.5$  (McDonald et al. 2006; Slosar et al. 2011).

BOSS is a spectroscopic survey undertaken within the SDSS-III program (Eisenstein et al. 2011b). SDSS-III uses a dedicated 2.5-m telescope located at the Apache Point Observatory in New Mexico at an elevation of 2788 m (Gunn et al. 1998, 2006). In this work, I am using data that will be part of the SDSS Data Release (DR9), which will include all the observations taken by the BOSS prior to the summer shutdown in July 2011 and is released in July of 2012.

### 2.4.2 Quasars

BOSS targets galaxies for its main BAO survey and quasars for studies of the Lyman- $\alpha$  forest. Maximizing the number of quasar sight-lines, regardless of how the quasars are selected, is the best way to detect the baryon acoustic feature in the Lyman- $\alpha$  forest, which is a goal of BOSS.

It was recognized early on in the survey, however, that additional science can be done with a *homogeneous* quasar sample, such as, determinations of the quasar luminosity function, active black hole mass function, and auto-correlation function. Thus, to maximize the scientific output of the survey, the BOSS project decided to target half of the quasar sample

using a uniform selection algorithm (Ross et al. 2012). This subset of the quasar data is known as the “CORE” sample. On average, approximately 40 fibers for quasars targets were allocated per  $\text{deg}^2$  of the BOSS survey; 20 of these fibers are used for the CORE sample and another  $\sim 20$  targets are from the “BONUS” sample. The BONUS sample uses targeting algorithms that incorporate all available information, even if it is heterogeneous on the sky, and is continually updated to maximize the number of quasars observed without regard to uniformity of selection. After initial experimentation with different selection algorithms (see, e.g., Kirkpatrick et al. 2011), the algorithm denoted “XDQSO” was finalized as the algorithm that defines the CORE sample for the rest of the survey. The details of the XDQSO targeting algorithm are presented in Bovy et al. (2011).

The main goal of having a separate homogeneous CORE sample is to enable statistical studies, which require understanding of the completeness of the survey. The work described in this chapter is one study that is possible because of this CORE sample.

The BOSS survey targeting strategy divides the sky into “chunks.” During the initial period, the targeting algorithm was held constant within each chunk and changed between chunks. After the chunk “boss12”, the targeting algorithm for CORE was frozen, So the BOSS CORE sample is homogeneously selected subsequent to chunk 12, and will remain so until the end of the survey. Ross et al. (2012) provides the details of the quasar target selection and quasar sample. For this study, we are using all BOSS chunks except boss1, which was Stripe 82 (Stoughton et al. 2002) commissioning data. Fig 2.3 shows the redshift distribution of the quasars in our study.

### 2.4.3 Random Catalog for Quasars

The construction of random catalogs that represent the selection of BOSS CORE quasars is detailed in White et al. (2012). Because the CORE quasar target selection was in flux for the first-year, the CORE quasar sample is not perfectly uniform. However, as the CORE target selection algorithm is now fixed to XDQSO, the completeness of the first year data can be estimated retroactively. For each chunk, we take the catalog of targets XDQSO would have generated and compare it to the objects that were actually observed. From

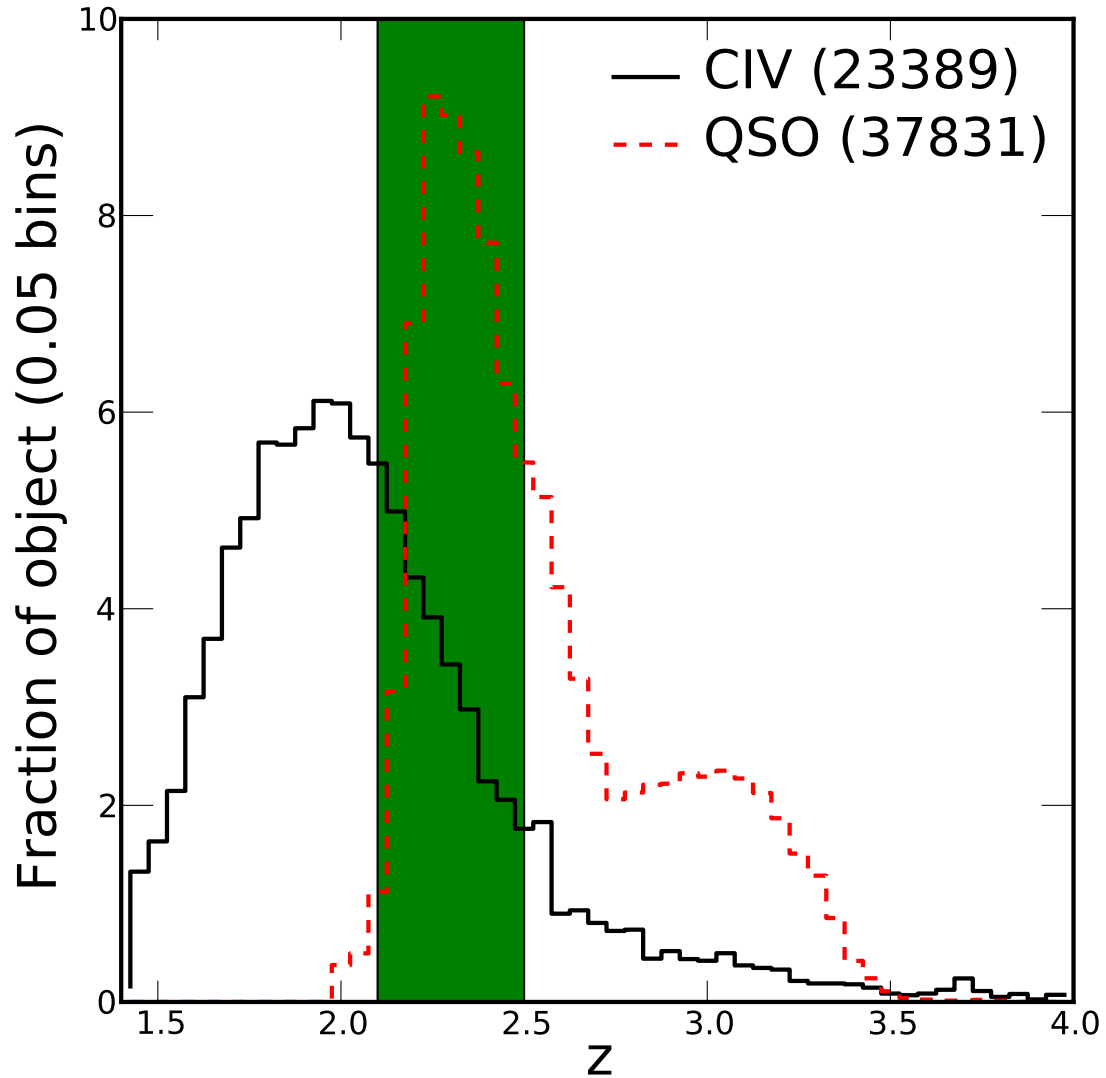


Figure 2.3 Distribution of redshift for C IV absorbers (black, solid line) and quasars (red, dashed). All quasars are from the CORE DR9 sample. There are a total 37,831 quasars and 23,389 C IV absorbers in the sample. However, our clustering analysis only makes use of the 19,701 quasars and 6,149 absorbers of equivalent width  $> 0.28\text{\AA}$  in the overlapping region of the distributions from  $2.1 < z < 2.5$ .

this comparison, I calculate the completeness of each sector, where a sector is a spherical polygon, or a collection of spherical polygons, that define a survey area observed under the same conditions. Fortunately, there is a high coincidence of target objects between the XDQSO targets and the actual targets observed for a given chunk. [Ross et al. \(2012\)](#) presented the details and a comparison of the target selection algorithms.

To reconstruct the correlation function, I need a random sample subject to the same survey effects as the quasar sample. I used code written by Adam Meyers to calculate completeness and generate the random sample. I generated a random sample with approximately 100 times more random points the actual number of quasars to accurately sample the completeness in redshift and position on the sky. Therefore, the random sample represents an unclustered distribution of points following the properties of the data. The random generation, completeness mask, and redshift distribution are described in detail in [White et al. \(2012\)](#).

#### 2.4.4 C IV Absorption line identification pipeline

The C IV absorbers examined in this work were extracted using a modified version of the automated SDSS Data Release 7 ([Abazajian et al. 2009](#)) quasar absorption line identification pipeline described in [Lundgren et al. \(2009\)](#) and [York and et al. \(2012, in prep\)](#). The pipeline identifies features of absorption by first subtracting a pseudo-continuum from each quasar. In each case, the pseudo-continuum is determined using a variation of a moving mean, which has been found to robustly fit both the quasar emission lines and the flat regions over a broad range of quasar spectral morphologies. An algorithm is then run on the normalized spectra to identify significant absorption lines. The line-finding algorithm determines the reduced  $\chi^2$  fit to a Gaussian profile centered on each pixel of the spectrum. Errors on the equivalent width of each feature are measured directly from the error array of the quasar spectra output by the BOSS pipeline, and lines with  $\geq 3\sigma$  significance are retained for identification. The error on the equivalent width reflects the  $1\sigma$  error on the best Gaussian fit to each absorption line, as derived from the SDSS error spectrum (photon statistics) for each object. For the rest frame equivalent width measurements, the observed error is divided by  $1 + z$ .

The pipeline then attempts to identify each of the detected absorption features by matching ions of different species at the same redshift. The line identification algorithm operates by first identifying the most easily observable doublets, C IV and Mg II. The search is done independently for each of these doublets, so systems that only have C IV or only have Mg II are easily found. Since absorbing gas should be physically located in the foreground of the quasar, this search is restricted to the wavelength range corresponding to a velocity of  $3000 \text{ km s}^{-1}$  behind the quasar, to accommodate redshift errors in the quasar sample.

The continuum fitting algorithm fits poorly around narrow emission lines, causing it to often produce artifacts of false absorption features. For this reason, the algorithm also omits regions of the quasar spectrum in close proximity ( $20 \text{ \AA}$ ) to narrow emission lines. Because of our cross-correlation analysis approach, our study is not sensitive to any underestimation of C IV absorbers caused by narrow emission lines.

For each detected doublet, an absorption redshift is determined, and the remaining unidentified absorption lines are examined for matches to other ions at the same redshift. I consider all C IV absorbers that have resolved doublets detected at  $\geq 4\sigma$  significance.

#### 2.4.5 The C IV sample

I use the pipeline described in §2.4.4 to find C IV absorbers in BOSS quasar spectra. As explained in §2.4.2, there are two samples of quasars, CORE and BONUS. However, the absorber sample does not need to use a well defined selection of quasars. I choose C IV absorbers in the following redshift range:

$$\begin{aligned} z_{\text{abs}} &< \min \left( \sqrt{\frac{1 - \beta_{\text{min}}}{1 + \beta_{\text{min}}}} (1 + z_{\text{QSO}}) - 1, \frac{7500 \text{ \AA}}{1549 \text{ \AA}} - 1 \right) \\ z_{\text{abs}} &> \max \left( \frac{1260 \text{ \AA}}{1549 \text{ \AA}} (1 + z_{\text{QSO}}) - 1, \frac{3800 \text{ \AA}}{1549 \text{ \AA}} - 1 \right) \end{aligned} \quad (2.9)$$

As evident from Eq. 2.9 I choose the C IV absorbers in the quasar spectra in the observed wavelength range of  $3800\text{--}7500 \text{ \AA}$ . This range is chosen to avoid the noisy region of the spectra due to spectral contamination from sky lines and our limited ability to correct for them. I also avoid any features in the region shortwards of  $1260 \text{ \AA}$  in the quasar rest-frame, as this region is contaminated by the N V line and the Lyman- $\alpha$  forest. Therefore, our cut

avoids many potential false detections at the expense of missing some real systems. This approach leads to a redshift range for detectable C IV absorbers of  $1.453 < z_{\text{abs}} < 3.841$ .

Broad Absorption Lines (BALs) in quasar spectra are known to contaminate Narrow Absorption Lines (NALs), so all spectra with C IV BALs are removed from our analysis. The BOSS quasar catalog relies on visual examination to determine if an object is a quasar or not. BAL absorbers are visually identified in all cases (Pâris 2012). This process leads to a first-cut catalog of 37,441 C IV absorbers.

Our aim is to study the clustering of C IV absorbers relative to quasars. Quasars are known to emit ionized winds at high velocity, so many absorption features in quasar spectra will be intrinsic to the quasar itself rather than due to intervening absorbers. To remove these intervening absorbers, I apply an additional constraint of  $\beta > 0.02$  with  $\beta$  given by

$$\beta = \frac{v}{c} = \frac{(1 + z_{\text{QSO}})^2 - (1 + z_{\text{abs}})^2}{(1 + z_{\text{QSO}})^2 + (1 + z_{\text{abs}})^2}, \quad (2.10)$$

The quantity  $\beta$  is the recession velocity between absorber and quasar. The cut of  $\beta = 0.02$  corresponds to  $v = 6000 \text{ km s}^{-1}$  which removes most of the intrinsic absorbers from the sample. Previous studies used a less conservative cut for the velocity. Ellison et al. (2002) used  $3000 \text{ km s}^{-1}$  and Fox et al. (2007) used  $5000 \text{ km s}^{-1}$ .

Figure 2.4 shows the distribution of  $\beta$  for our sample. The excess of C IV absorbers in  $0 < \beta < 0.02$  is due to intrinsic C IV absorbers, which I remove from our sample. Intrinsic C IV absorbers are known to contaminate the sample at much larger velocities (vanden Berk et al. 1996; Richards et al. 1999). Such contamination may affect the estimation of the correlation function; I estimate this effect in §2.7.4. The intrinsic absorbers may reside in the host galaxy of the quasar, be in material ejected from the quasar, or be in the clustering environment of the quasar. Only the material ejected by the quasar, however, can contaminate the measurement of the correlation function. All other sources of intrinsic C IV absorbers would still contribute to the correct correlation function. To accurately describe intrinsic absorbers, I would have to assume a model for the velocity distribution around the quasar, but such a study is beyond the scope of this current work. Applying the  $\beta > 0.02$  cuts decreases our C IV absorber sample to 23,339 absorbers.

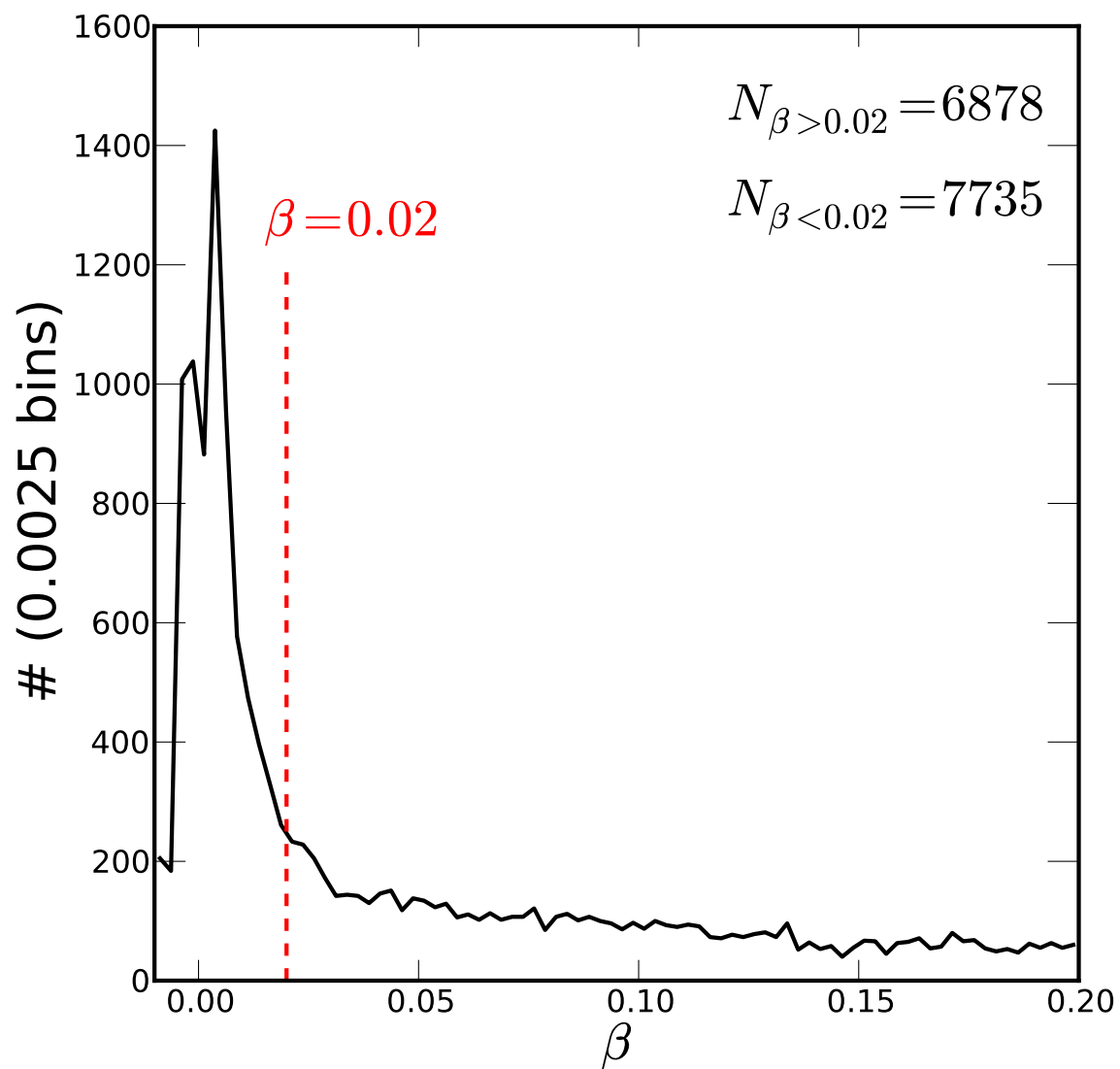


Figure 2.4 Distribution of  $\beta$  of the absorbers. The excess in the range  $0.0 < \beta < 0.02$  is due to absorbers intrinsic to the quasar. The red dashed line of  $\beta = 0.02$  separates the samples in our study. After the  $\beta$  cut, 23,389 absorbers remain.



I measure the equivalent width of the doublet as the equivalent width of the 1548Å line. Catalog absorbers with rest-frame equivalent widths,  $W_r$ ,  $\approx 5$  Å can arise as artifacts of the pipeline (due to, for example, poorly subtracted night sky lines) or from complicated blends of multiple doublets. All absorbers with such strong  $W_r > 5$  Å features are removed from the sample. This limit removes only 15 absorbers from our sample, leaving 23,324 absorbers.

The likelihood of false positives is higher in the small observer-frame equivalent width absorbers, so I apply a cut on observer-frame equivalent width of  $W_0 > 1$  Å. Applying this cut provides an automatic cut on rest-frame equivalent width of  $W_r > 0.28$ Å (at our median sample redshift of  $z \sim 2.3$ ). Figure 2.5 shows the distribution of absorbers in  $i$ -band magnitude and  $W_r$  space. The top panel shows the distribution of  $W_r$  for absorbers from CORE and BONUS quasars. The side panel shows the distribution of  $i$ -band magnitude for the same absorbers. After applying this cut, I am left with 20,925 absorbers.

Cross-correlating BOSS quasars and absorbers on scales out to 100 Mpc requires the two samples to be in the same redshift range ( $2.1 < z \leq 2.5$ ). There are very few quasars at  $z < 2.1$  and few absorbers at  $z > 2.5$ . This redshift range restricts our final sample to 6,149 C IV absorbers, which is almost an order-of-magnitude larger than previous C IV absorbers correlation analyses. A summary of the effects of the different cuts is given in Table 2.1.

## 2.5 CORRELATION ANALYSIS

The spatial correlation function,  $\xi(r)$ , describes the clustering of spatial points as a function of distance  $r$ . Similarly, the cross-correlation function,  $\xi_{A-B}$ , describes the clustering of two species A and B at any given separation  $r$ . The cross-correlation function between a population of C IV absorbers and of quasars,  $\xi_{\text{QSO-CIV}}(r)$ , is defined as the excess probability of finding a C IV absorber at distance  $r$  from a quasar compared to the chance of a random coincidence:

$$dP(r) = \bar{n}_{\text{QSO}}\bar{n}_{\text{CIV}} (1 + \xi_{\text{QSO-CIV}}(r)) dV_{\text{QSO}} dV_{\text{CIV}} \quad (2.11)$$

where  $\bar{n}_{\text{CIV}}$  is the mean density of C IV absorbers, and  $\bar{n}_{\text{QSO}}$  is the mean density of quasars (Peebles 1980).

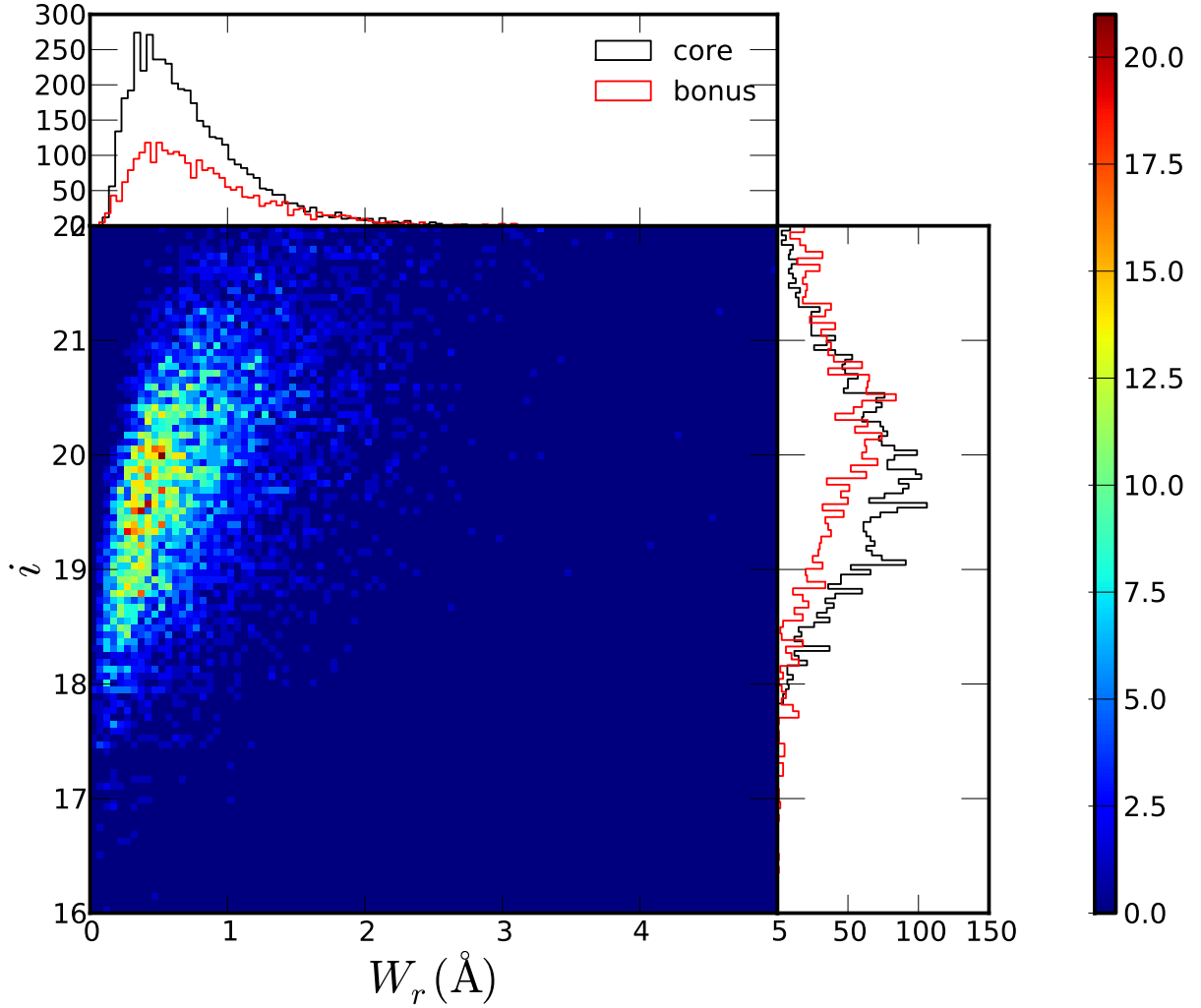


Figure 2.5 The bottom left panel of the plot shows the distribution of C IV absorber rest-frame equivalent width,  $W_r(\text{\AA})$ , and the quasar  $i$ -band magnitude. The color denotes the number density of the C IV absorbers. The color-bar at the right side of the plot shows the color-density scale. The lack of completeness for low  $W_r$  is evident as it is systematically more difficult to detect weaker absorbers in fainter quasars. The panel at the right shows the distribution of  $i$ -band magnitude for absorbers from the CORE and BONUS quasar samples. Similarly, the panel at the top shows the distribution of  $W_r$  for absorbers from the CORE and BONUS quasar sample.

Table 2.1 Table of Number of C IV absorbers for different selection cuts

Description	Number of C IV absorbers
No cut	37,441
$\beta > 0.02$	23,339
$W_r < 5 \text{ \AA}$	23,324
$W_o > 1 \text{ \AA}$	20,925
$2.1 < z \leq 2.5$	6,149

The non-continuous geometry and varying depth of observations in large surveys makes the task of estimating the correlation function more difficult than the trivial calculation of distances between different pairs. In general, the estimation of the correlation function relies on constructing a random sample which contains all the information about the geometry of the survey and the varying depth of data by calculating the completeness of the observation in any given sector. This random sample is essentially a mock survey that does not have any clustering but contains all of the other information about the survey that needs to be considered for a correlation function calculation. By comparing the clustering of real data and the random sample, the real clustering of the data can be isolated and measured .

There are different estimators for the correlation function, each of which has advantages and disadvantages in the context of our study. The first method I consider is from [Peebles \(1980\)](#),

$$\xi_{\text{QSO-CIV}}(r) = \frac{D_{\text{CIV}} D_{\text{QSO}}}{D_{\text{CIV}} R_{\text{QSO}}} - 1, \quad (2.12)$$

where  $D_{\text{QSO}}$  represents our CORE sample of quasar data,  $R_{\text{QSO}}$  is the random sample that corresponds to the quasars and  $D_{\text{CIV}}$  is CIV absorber data.  $DD$  and  $DR$  represent the data-data and data-random pair counts as a function of  $r$ . The auto-correlation of quasars is defined in a similar manner to Eq. 2.12. The advantage of the estimator in Eq. 2.12 is that it does not need a random sample for the C IV absorbers. However, while this method is simple, it is a biased estimator ([Peebles 1980](#)).

The other method I consider for estimating the cross-correlation function is an unbiased

estimator given by [Landy and Szalay \(1993\)](#),

$$\xi_{\text{QSO-CIV}}(r) = \frac{D_{\text{CIV}}D_{\text{QSO}} - R_{\text{CIV}}D_{\text{QSO}} - D_{\text{CIV}}R_{\text{QSO}} + R_{\text{CIV}}R_{\text{QSO}}}{R_{\text{CIV}}R_{\text{QSO}}}, \quad (2.13)$$

where  $D_{\text{QSO}}$  and  $R_{\text{QSO}}$  are the same as in the previous equation and  $D_{\text{CIV}}$  and  $R_{\text{CIV}}$  are the C IV absorber sample and random sample for the C IV sample.

Eq. 2.13 is a more robust estimator, but it would require the generation of a reliable CIV absorber random catalog. While I use Eq. 2.12 in this analysis, I would like to share some thoughts on Eq. 2.13, as it may become the preferred method for future analyses.

The established procedure to generate random absorbers is to select a random point in the sight line to the quasar in the range that absorbers could be detected. However, this approach is not an accurate way to generate the random absorbers, as it assumes the chances of detection and number density of the absorbers to be constant along the line-of-sight. If the sight line covers a large enough redshift range, this assumption would affect the observed number density of absorbers. Other effects, such as gravitational lensing, may contribute to changes in the observed number density of the absorbers as well. I propose that future analysis based an approach that uses Eq. 2.13 use a different two-step procedure. First, a random quasar sample should be generated, which provides the locations on the sky. Second, absorbers should be assigned redshifts, drawing from the observed redshift distribution of the absorbers. This distribution may be a function of completeness of the survey. This procedure would yield two advantages over our current use of Eq. 2.12; it would not have to make any assumption about the evolution of number density and probability of detection, and it will reduce the effect of survey edges on the correlation function.

However, I can not use Eq. 2.13 because I need a larger sample of absorbers to estimate the redshift distribution for different completeness bins of quasars. At the conclusion of the BOSS survey, it will cover a large footprint with high completeness, and we will be able to generate a random sample that accurately follows the absorber population.

For the current study, I choose the estimator in Eq. 2.12, which does not require random absorbers for C IV.

In addition to redshift-space three dimensional correlation fuction, I also calculate the projected cross-correlation function for the C IV absorbers and quasars. The redshift-space

distance,  $s$ , between a C IV absorber and quasar can be decomposed into components perpendicular ( $r_p$ ) and parallel ( $\pi$ ) to the line of sight

$$s^2 = r_p^2 + \pi^2. \quad (2.14)$$

I can estimate the two-dimensional cross-correlation function as

$$\xi(r_p, \pi) = \frac{D_{\text{CIV}} D_{\text{QSO}}(r_p, \pi)}{D_{\text{CIV}} R_{\text{QSO}}(r_p, \pi)} - 1 \quad (2.15)$$

and the projected cross-correlation function is defined as

$$w_p(r_p) = 2 \int_0^\infty \xi(r_p, \pi) d\pi \quad (2.16)$$

### 2.5.1 Error Estimation

Correlation function studies have used different methods of error estimation. These methods can be broadly placed in three categories: Poisson, Field-to-Field, and Jackknife. The Poisson error is simplest, but it assumes that the pair counts on different distance scales are independent. However, the Poisson error is known to underestimate the error at large distances, where the Poisson error is small and the cosmic variance term becomes comparable or bigger than the Poisson error (Myers et al. 2005; Ross et al. 2007), such that the Poisson counts are correlated across different scales. In this study, I choose to use the jackknife method, following Scranton et al. (2002).

I partition the data into 25 different areas which have roughly the same number of quasars from our random quasar catalog. I calculate 25 separate cross-correlation functions, leaving out one chunk at a time. Using the 25 cross-correlation functions, I estimate the covariance matrix from

$$\text{Cov}_{ij} = \frac{N-1}{N} \sum_{i=1}^N (\bar{\xi}(r_i) - \xi(r_i)) (\bar{\xi}(r_j) - \xi(r_j)) \quad (2.17)$$

where  $N = 25$  is the number of cross-correlation functions,  $r_i$  and  $r_j$  are the points where the correlation function are estimated, and  $\xi(r_i)$  is the correlation function for the full sample at  $r_j$ . The diagonal element of the covariance matrix  $\text{Cov}_{ii}$  is the error estimate for the variance  $\sigma_{ii}^2$  of the two-point correlation function in the  $i^{\text{th}}$  bin.

### 2.5.2 Fitting for the Correlation Function and Bias

A standard way to model the two-point correlation function is using a power law given by

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma} \quad (2.18)$$

which is a good approximation for the correlation function to large distances and also a convenient form to compare with other results. The assumption of a power-law form for the correlation function in real space leads to a projected-space correlation function, defined in Eq. 2.16, of the following form

$$\frac{w_p}{r_p} = \left(\frac{r_0}{r_p}\right)^\gamma B\left(\frac{1}{2}, \frac{\gamma-1}{2}\right) \quad (2.19)$$

where  $B(a, b)$  is the Euler beta function. In reality, I can not integrate in the line-of-sight direction to infinity. If I choose to select the maximum line-of-sight distance,  $\pi_{\max}$ , as our integration limit, I can write

$$\frac{\dot{w}_p}{r_p} = \left(\frac{r_0}{r_p}\right)^\gamma \left[ B\left(\frac{1}{2}, \frac{\gamma-1}{2}\right) - B\left(\frac{r_p^2}{r_p^2 + \pi_{\max}^2}; \frac{1}{2}, \frac{\gamma-1}{2}\right) \right] \quad (2.20)$$

where  $\dot{w}_p$  is the projected correlation function integrated to  $\pi_{\max}$  and  $B(z; a, b)$  is the incomplete beta function.

To fit the correlation function in the above form, I minimize

$$\chi^2 = [\xi - \hat{\xi}]^T \text{Cov}^{-1} [\xi - \hat{\xi}] \quad (2.21)$$

where  $\hat{\xi}$  is value from the model. However, in general, the covariance matrix is too noisy to be useful, so I only use the diagonal element of the covariance matrix.

Baryonic matter traces the gravitational potential created by dark matter and scales as a function of the dark matter (DM) halo mass (Bardeen et al. 1986; Cole and Kaiser 1989; Mo and White 1996; Sheth and Tormen 1999; Sheth et al. 2001; Jing 1998; Gao and White 2006; Tinker et al. 2010). The observed two-point correlation function of baryonic material is related to the underlying dark matter two-point correlation function, as explained in §2.2. If I assume a linear bias (Scherrer and Weinberg 1998), or baryon/DM ratio, then I can write

$$\xi_{\text{CIV-QSO}}(r) = b_{\text{CIV}} b_{\text{QSO}} \xi_{\text{DM}}(r), \quad (2.22)$$

$$\xi_{\text{QSO-QSO}}(r) = b_{\text{QSO}}^2 \xi_{\text{DM}}(r), \quad (2.23)$$

similar to Eq. 2.7. I can thus find the bias for C IV absorbers without knowing the underlying dark matter two-point correlation function. In terms of the other observable quantities  $\xi_{\text{QSO-QSO}}$  and  $b_{\text{QSO}}$ , the C IV absorber bias is

$$b_{\text{CIV}} = \frac{\xi_{\text{CIV-QSO}}}{\xi_{\text{QSO-QSO}}} b_{\text{QSO}} \quad (2.24)$$

The bias of a dark matter halo as a function of mass can be derived theoretically (Bardeen et al. 1986; Cole and Kaiser 1989; Mo and White 1996; Sheth and Tormen 1999; Sheth et al. 2001), but more accurate descriptions of halo bias can be derived from large-scale dark matter simulations (Jing 1998; Gao and White 2006; Tinker et al. 2010). Using such a calibration of the dark matter halo bias, I can find the mass of the dark matter halo in which a typical C IV absorber resides.

## 2.6 RESULTS

Table 2.2 summarizes our measurements of the correlation length and slope for the C IV absorber and quasar correlation functions.

### 2.6.1 Cross Correlation of C IV absorbers and quasars

Figure 2.6 presents our calculated three-dimensional cross-correlation of C IV absorbers and quasars in redshift space in the redshift range of  $2.1 < z < 2.5$ . Fitting the cross-correlation in the range of  $10 \text{ Mpc} < s < 100 \text{ Mpc}$  with a power law, as described in Eq. 2.18, I find the correlation-length to be  $s_o = 8.46 \pm 1.46 \text{ Mpc}$  with a slope  $\gamma = 1.68 \pm 0.27$ . For the fit I found  $\chi^2/\text{D.o.f} = 10.88/8 = 1.36$ , which suggests it is a quite reasonable fit to the data. However, there is significant degeneracy between the parameters  $s_o$  and  $\gamma$ , as changes due to an increase in slope can be caused by the increase of correlation length. The correlation coefficient between  $s_o$  and  $\gamma$  for our fit is 0.86, which suggests a high degree of correlation.

The cross-correlation measurement is expected to be not accurate in the range of  $s < 10$  Mpc, because at this scale, fiber collision is expected to contaminate the astrophysical clustering signal (Ross et al. 2009).

Figure 2.7 presents the projected cross-correlation of the C IV absorbers and quasars in the same redshift range  $2.1 < z < 2.5$ . I fit the cross-correlation in the range of  $10 \text{ Mpc} < r_p < 100 \text{ Mpc}$  with a power law, as described in Eqs. 2.19 & 2.20. I find the best fit power-law length to be  $r_0 = 7.76 \pm 3.80 \text{ Mpc}$  with a slope  $\gamma = 1.74 \pm 0.21$ . I integrate the correlation function in the line-of-sight direction until  $\pi_{\text{max}} = 60 \text{ Mpc}$  and find a  $\chi^2/\text{D.o.f} = 9.20/8 = 1.15$ . The estimates of the length scale and power-law slope are highly degenerate as indicated by a correlation coefficient of 0.96.

### 2.6.2 Cross-Correlation at large distance

Figure 2.8 shows the correlation function in the range of  $10 \text{ Mpc} < s < 1000 \text{ Mpc}$  in bins of 10 Mpc. The errors are Poisson errors. The blue line is the best-fit cross-correlation function. I find that the power-law fit does not fit the data for distances  $s > 100 \text{ Mpc}$ . This disagreement is potentially expected as there is no reason the correlation function should be well-approximated by a power-law at large distances, but this measurement provides quantitative confirmation of the significant variation from the simple power-law model. Both the observed and simple models for the correlation function gradually approach zero at larger distances. Cosmic variance can contribute a small offset from zero at all scales, which is evident only at large scales when the correlation is very close to zero.

### 2.6.3 Estimation of C IV bias

One of the major aims of this work is to calculate the bias of C IV absorbers with respect to linear matter perturbations. I use a cross-correlation between the QSO sample and the C IV sample to best estimate this bias. Ideally, one would use the C IV auto-correlation, but the appropriate random set for the QSO sample is far better understood than for the C IV sample. A proper generation of randoms for the absorber sample would require a model of the evolution and distribution of C IV absorbers as a function of redshift. Providing rough



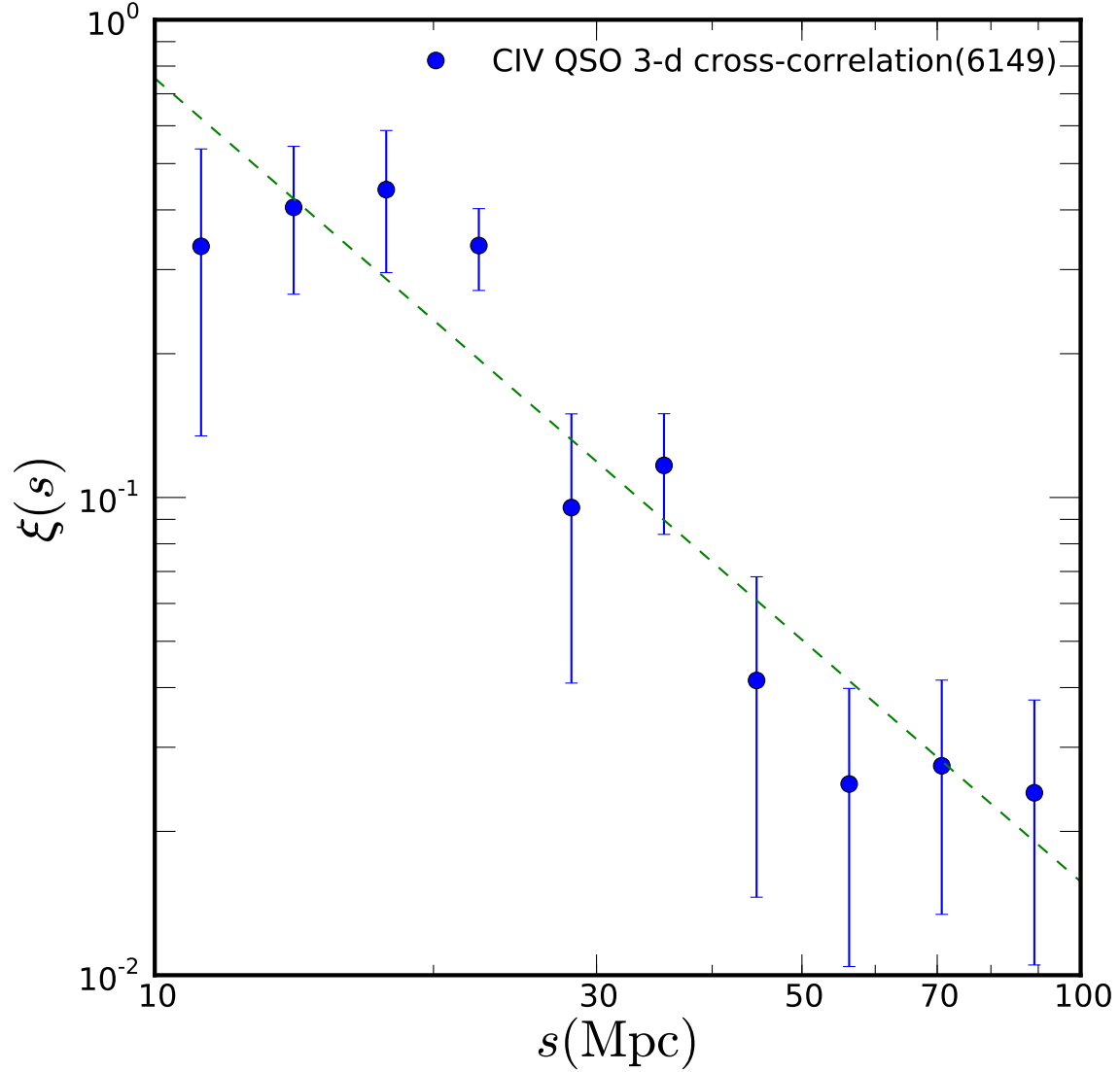


Figure 2.6 Cross-correlation function in redshift space for C IV absorbers and quasars from  $2.1 < z < 2.5$ . The dotted line is the best-fit power law, as defined in Eq. 2.18, with  $s_o = 8.46 \pm 1.46$  Mpc and slope  $\gamma = 1.68 \pm 0.27$  in the range  $10 \text{ Mpc} < s < 100 \text{ Mpc}$ . The horizontal axis denotes the geometric mean of the bin distance. The vertical error bar is the jackknife error.

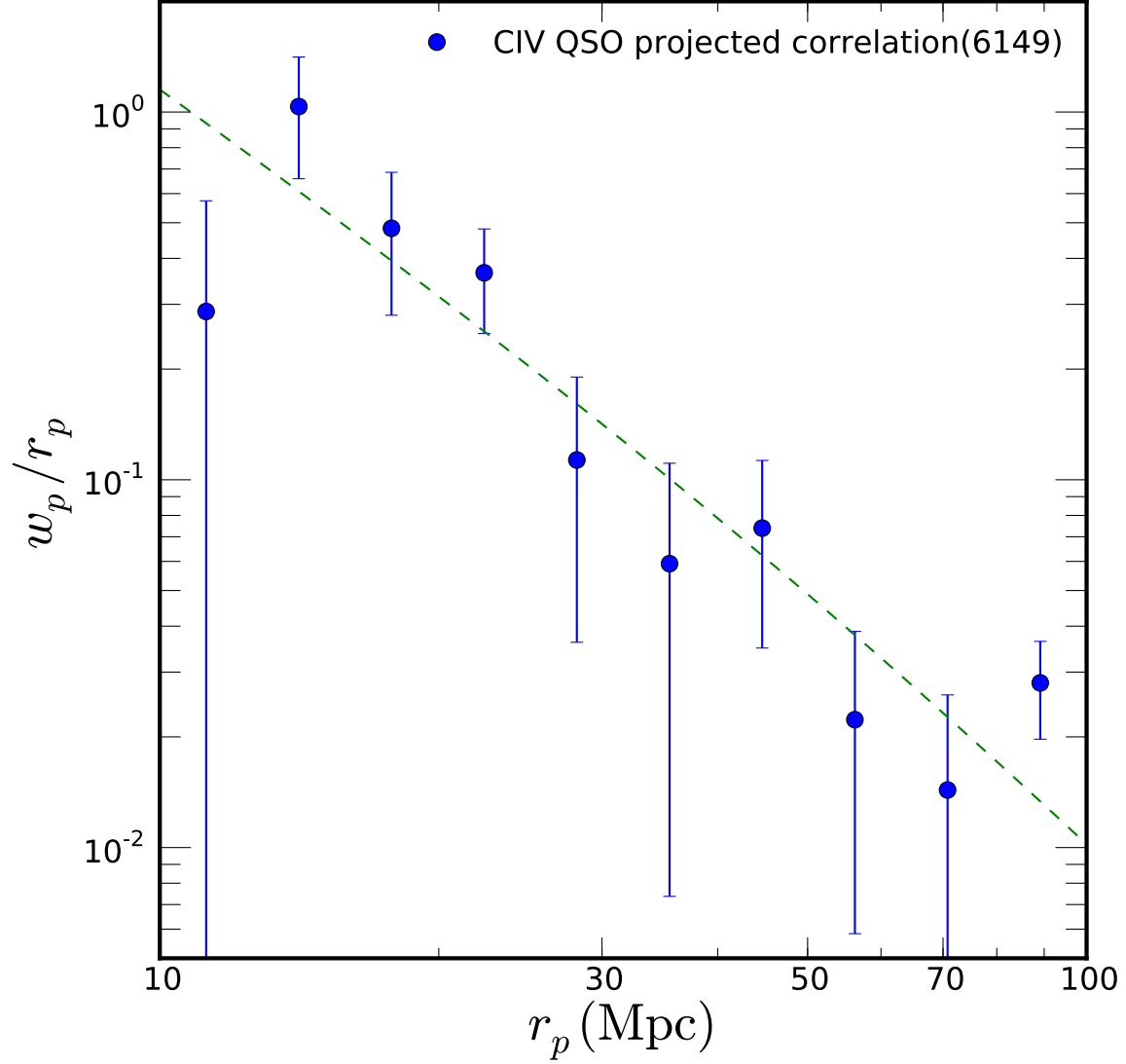


Figure 2.7 Projected correlation function for C IV absorbers and quasars. The dotted line is the best fit power law, as defined in Eqs. 2.19 and 2.20, with  $r_0 = 7.76 \pm 3.80$  Mpc and slope  $\gamma = 1.74 \pm 0.21$  in the range  $10 \text{ Mpc} < r_p < 100 \text{ Mpc}$ . The horizontal axis denotes the geometric mean of projected distance bin. The redshift range for the C IV absorbers and quasars is  $2.1 < z < 2.5$ .

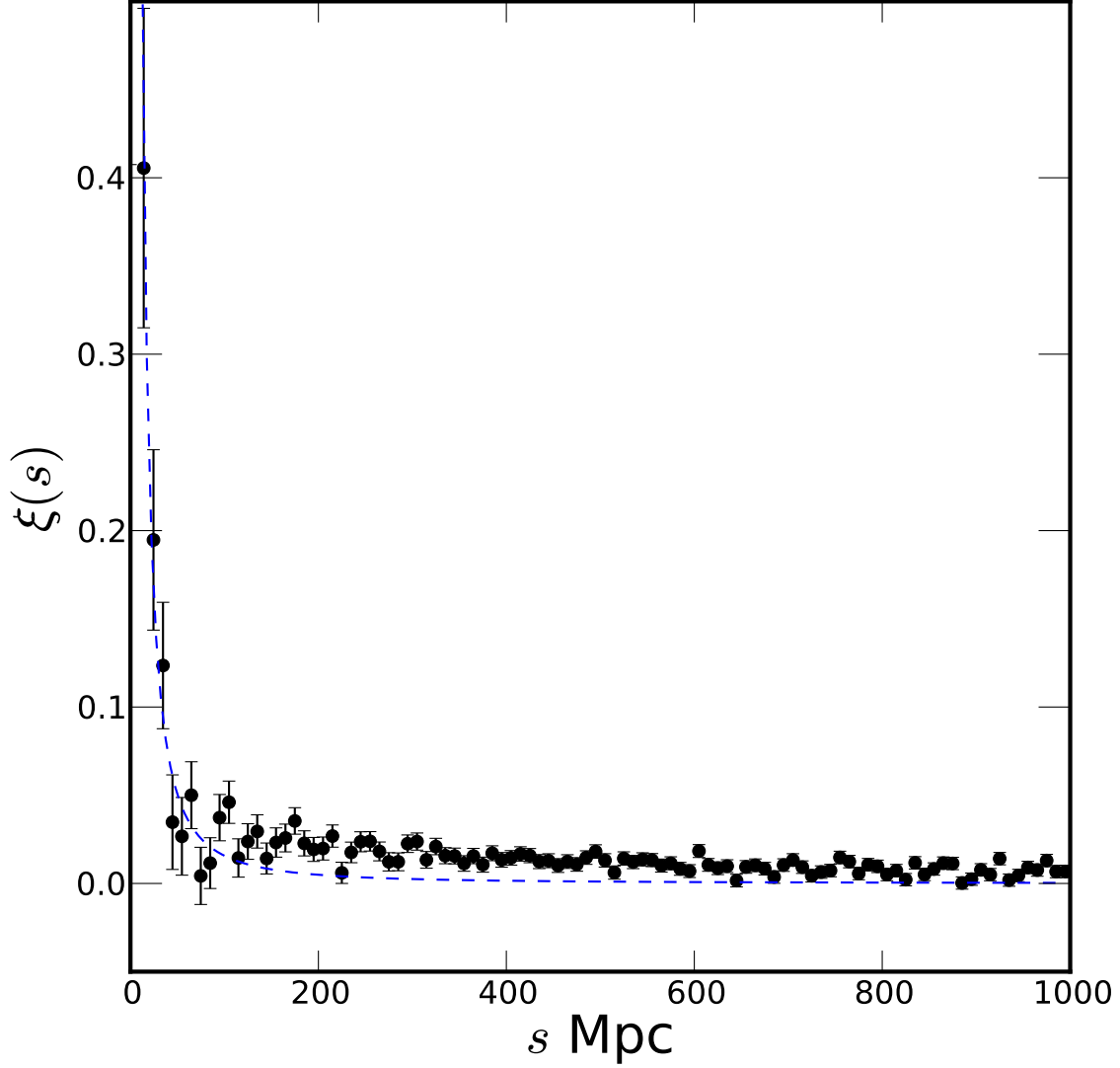


Figure 2.8 Correlation function for  $10 \text{ Mpc} < s < 1000 \text{ Mpc}$  with a bin size of  $10 \text{ Mpc}$ . The errors are calculated using Poisson re-sampling. The redshift range for the data is  $2.1 < z < 2.5$ . The blue dash-dot line is the best fit power law  $s_o = 8.46 \pm 1.46 \text{ Mpc}$  and  $\gamma = 1.68 \pm 0.27$ . This power law approximation significantly under-predicts the correlation at distances  $s > 100 \text{ Mpc}$  and I conclude it is invalid at this scale.

Table 2.2 The correlation length and slope for the different sample of C IV absorbers and quasars.

Description	$s_o r_o$ (Mpc)	$\gamma$
CIV-QSO 3D corr.	$8.46 \pm 1.46$	$1.68 \pm 0.27$
CIV-QSO projected corr. ( $r_o$ )	$7.76 \pm 3.80$	$1.74 \pm 0.21$
QSO-QSO 3D corr.	$12.19 \pm 0.32$	$1.77 \pm 0.04$
CIV-QSO 3D corr. ( $\gamma = 1.77$ )	$8.92 \pm 0.63$	fixed at 1.77

constraints for such a model is one of the goals of current work, so I choose to avoid making assumptions about this distribution by using a QSO-CIV cross-correlation.

In order to use Eq. 2.24, I must calculate the bias for quasars,  $b_{\text{qso}}$ . The quasar bias is given by  $b_{\text{qso}}(z) = \xi_{\text{qso-qso}}(r, z)/\xi_{\text{dm}}(r, z)$ , where  $\xi_{\text{qso-qso}}(r, z)$  is the real-space correlation function of our quasar sample and  $\xi_{\text{dm}}(r, z)$  is the theoretical matter correlation function.

A full treatment of the BOSS quasar auto-correlation from 4–36 Mpc is given in [White et al. \(2012\)](#). Our analysis here is simpler, focused on the larger scale of 10–100 Mpc, to extract a reliable quasar bias to compute the C IV absorber bias. I use the same tools for the quasar random sample and completeness map as in [White et al. \(2012\)](#), but while that work required a completeness of  $> 0.75$ , I do not apply a completeness cut in order to use all of the C IV absorbers.

I follow the method adopted by [Ross et al. \(2009\)](#) to calculate quasar bias. I calculate the volume-average correlation function  $\bar{\xi}$ , defined as

$$\bar{\xi} = \frac{\int_{s_{\min}}^{s_{\max}} 4\pi \dot{s}^2 \xi(\dot{s}) d\dot{s}}{\int_{s_{\min}}^{s_{\max}} 4\pi \dot{s}^2 d\dot{s}} \quad (2.25)$$

$$= \frac{3}{(s_{\max}^3 - s_{\min}^3)} \int_{s_{\min}}^{s_{\max}} \xi(\dot{s}) \dot{s}^2 d\dot{s} \quad (2.26)$$

where  $s_{\min} = 10$  Mpc and  $s_{\max} = 100$  Mpc for our case. The volume-average correlation function minimizes non-linear effects. Instead of using the theoretical definition of the scale-independent bias is expressed in terms of the real-space clustering, I measure the redshift-

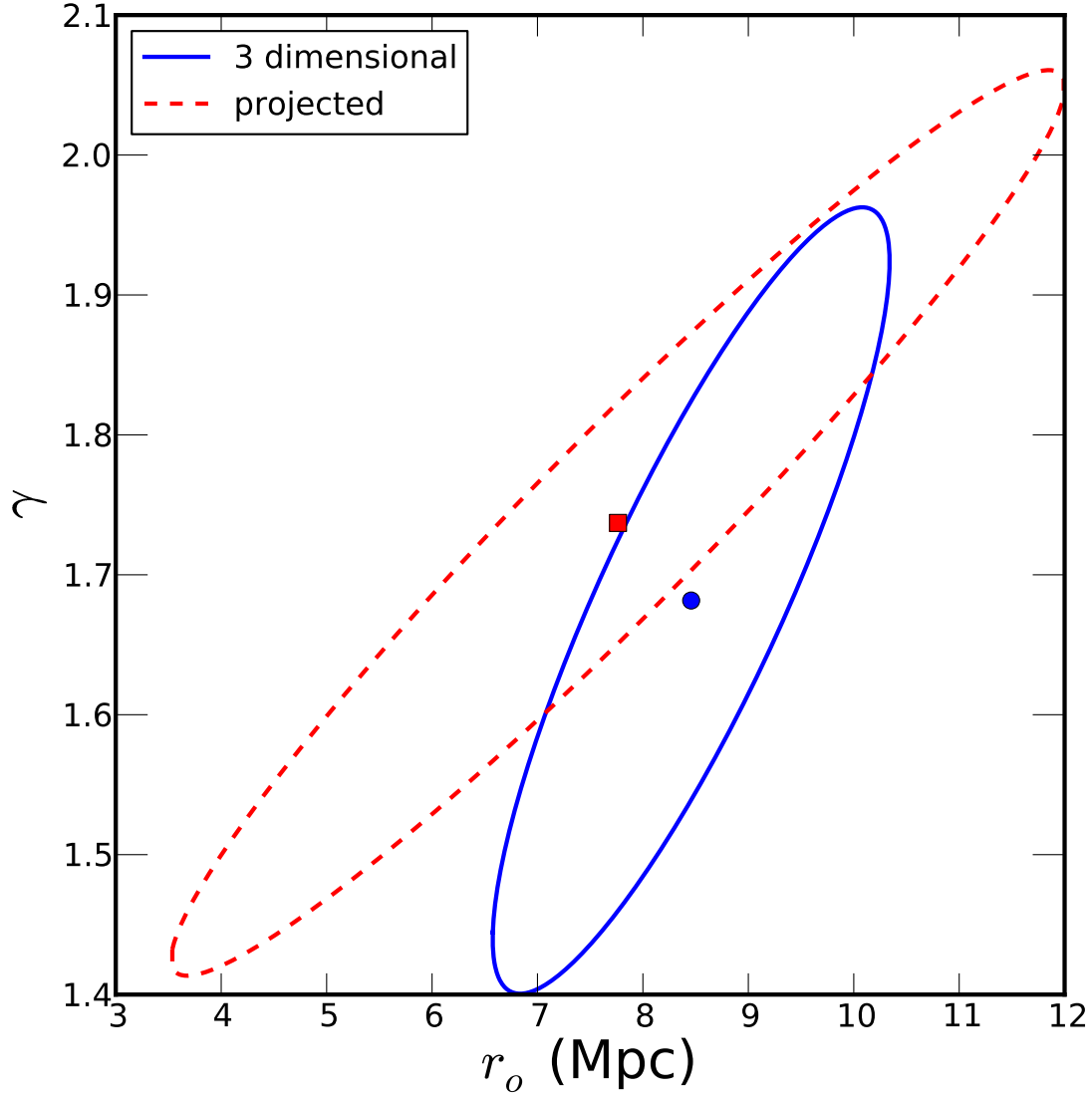


Figure 2.9 The correlation of  $r_0$  and  $\gamma$ . The solid blue line is the  $1\sigma$  contour region for a  $r_0$  and  $\gamma$  fit to the 3D correlation function and the dashed red line is the same for the projected correlation function. There is a strong degeneracy between the slope and scale length of both the 3D and the projected correlation functions.

space correlation function. To minimize the error caused by this difference, I use a linear-regime relation between the redshift-space and real-space correlation function given by

$$\xi(s) = \xi(r) \left( 1 + \frac{2}{3}\beta(z) + \frac{1}{5}\beta^2(z) \right) \quad (2.27)$$

where

$$\beta(z) = \frac{\Omega_m^{0.55}(z)}{b(z)}. \quad (2.28)$$

The difference in the real-space and redshift-space correlation functions is due to redshift distortion caused by infall of baryonic matter towards the over-density of matter (Kaiser 1987; Fisher et al. 1994; Peacock et al. 2001; Hawkins et al. 2003; Ross et al. 2007; Guzzo et al. 2008). Using Eqs. 2.10 & 2.27 and the definition of bias, I find the expression for bias to be

$$b_{\text{qso}}(z) = \sqrt{\frac{\bar{\xi}_{\text{qso-qso}}(s, z)}{\bar{\xi}_{\text{dm}}(r, z)} - \frac{4\Omega_m^{1.1}(z)}{45} - \frac{\Omega_m^{0.55}(z)}{3}} \quad (2.29)$$

where the volume-averaged  $\bar{\xi}_{\text{qso-qso}}$  is calculated from our measured  $\xi_{\text{qso-qso}}$ , and  $\bar{\xi}_{\text{dm}}$  is calculated from the theoretical estimate of  $\xi_{\text{dm}}$ . I calculate  $\xi_{\text{dm}}$  from the model of Smith et al. (2003) for a non-linear power spectrum of dark matter, which is quite accurate for the distance range we are considering.

To measure the bias for CIV absorbers, I use the above method and assume the same distortion for the CIV absorbers quasar cross-correlation as for the auto-correlation of quasars. The bias for cross-correlation can then be given by the following

$$\sqrt{b_{\text{qso}}b_{\text{CIV}}} = \sqrt{\frac{\bar{\xi}_{\text{CIV-qso}}(s, z)}{\bar{\xi}_{\text{dm}}(r, z)} - \frac{4\Omega_m^{1.1}(z)}{45} - \frac{\Omega_m^{0.55}(z)}{3}}. \quad (2.30)$$

Combining Eqs. 2.29 & 2.30, I can calculate the bias for the C IV absorbers..

Fig. 2.10 presents the auto-correlation function (black squares) for the BOSS DR9 quasars in the redshift range  $2.1 < z < 2.5$ , over the redshift-space distance range  $10 \text{ Mpc} < s < 100 \text{ Mpc}$ . The errors are calculated using the jackknife method. I fit the quasar auto-correlation with a power law and find the correlation length to be  $s_o = 12.19 \pm 0.32 \text{ Mpc}$  ( $8.78 \pm 0.23 h^{-1} \text{ Mpc}$ ;  $h = 0.72$ ) with a power-law slope  $\gamma = 1.77 \pm 0.04$ . This is comparable to  $9.7 \pm 0.5 h^{-1} \text{ Mpc}$ , found in White et al. (2012) for a fixed power-law slope of  $-2$  ( $\gamma = 2$ ). The power-law parameters  $s_o$  and  $\gamma$  are highly degenerate; higher estimates of  $\gamma$  lead to higher

estimate of  $s_o$  (see, e.g., Fig. 2.9). I estimate the correlation in the range of 10–100 Mpc while White et al. (2012) performed their measurement over 3–25  $h^{-1}$  Mpc (4.2–35.7 Mpc;  $h = 0.72$ ).

The slope of the quasar correlation function in Fig. 2.10 is roughly consistent with an assumption of linear bias, although the power-law model does not completely explain the data. I have not done any systematic error analysis for the QSO auto-correlation function, as the auto-correlation of quasars is not the aim of this work; I refer readers interested in this subject to White et al. (2012).

Fig. 2.10 also shows the cross-correlation function of C IV absorbers and quasars fit with the slope of the quasar auto-correlation. The correlation length of C IV absorber-quasar in this case is  $s_o = 8.92 \pm 0.63$  Mpc. Using the method described above, I find the combined bias is  $\sqrt{b_{\text{qso}} b_{\text{CIV}}} = 2.97 \pm 0.51$ . I estimate the bias for quasars to be  $b_{\text{qso}} = 3.71$ . Using the  $b_{\text{qso}}$  I determine the bias for C IV absorbers to be  $b_{\text{CIV}} = 2.38 \pm 0.82$ .

I use this C IV bias value to calculate the mass of the typical dark matter halo in which these C IV absorbers reside (see §2.5.2). Using the model described by Sheth and Tormen (1999), which provides a relationship between halo mass and the bias for a given redshift, I find that the minimum mass of the dark matter halo for moderate C IV absorbers ( $0.28\text{\AA} < W_r < 4\text{\AA}$ ) is  $M_{\text{CIV}} \approx 10^{12} M_{\odot}$  for our median redshift of  $z = 2.3$ . Moderate C IV absorbers are quite specifically more clustered than halos less massive than this. Because the mass function for dark matter halos has a steep negative slope for high mass halos ( $> 10^{12} M_{\odot}$ ), if moderate C IV absorbers were found in lower-mass halos, then the likely great numbers of such absorbers would have significantly diluted the correlation function I measured.

These results imply that the dark matter halos more massive than  $10^{12} M_{\odot}$  contains enough C IV gas to produce an absorption feature stronger than  $0.28\text{\AA}$  at  $z \sim 2.3$ . Less massive halos have less than  $W_r < 0.28\text{\AA}$  of C IV gas at this redshift.

#### 2.6.4 Comparison with previous results

There have been various previous studies of the correlations of C IV absorbers with quasars and galaxies. However, most of these studies concentrated on the correlation function at

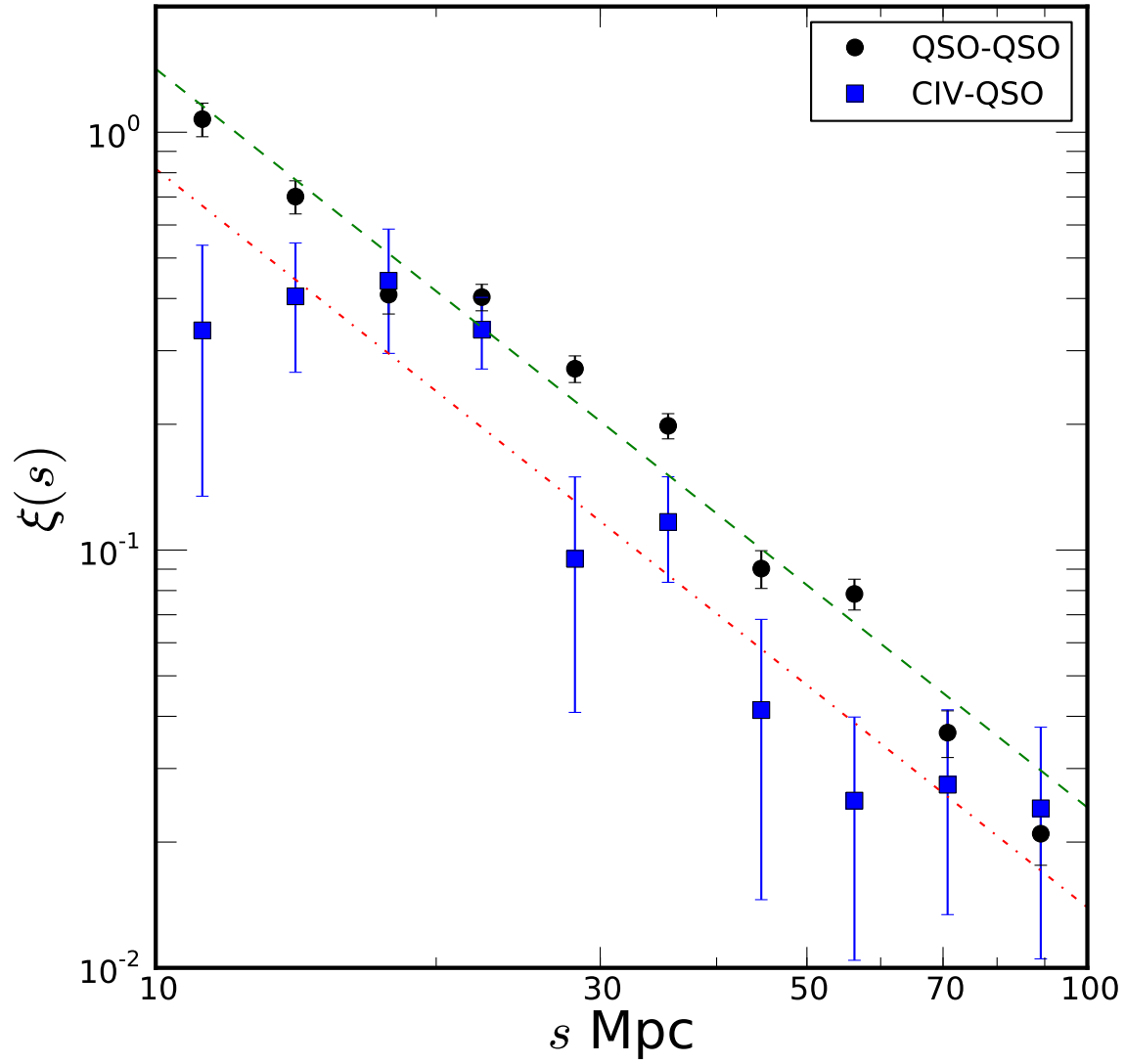


Figure 2.10 The quasar auto-correlation function (black circles). The green dashed line is the best power law fit in the range of  $10 \text{ Mpc} < s < 100 \text{ Mpc}$ . The redshift range for the data is  $2.1 < z < 2.5$ . The best-fit value for the power law is  $s_o = 12.19 \pm 0.32 \text{ Mpc}$  and slope  $\gamma = 1.77 \pm 0.04$ . The blue squares are the cross-correlation measurement for C IV absorbers and quasars over this redshift range. The red dash-dot line is the best-fit value for the correlation length,  $s_o = 8.92 \pm 0.63 \text{ Mpc}$ , assuming a fixed slope derived from the quasar auto-correlation.



much smaller distances than our study. [Wild et al. \(2008\)](#) quoted a correlation length of  $s_o = 5.8 \pm 1.1 h^{-1}$  Mpc with  $\gamma = -1.8$  for C IV absorbers with rest-frame  $W_r > 0.3\text{\AA}$ , compared to our result of  $s_o = 6.09 \pm 0.89h^{-1}$  Mpc ( $8.46 \pm 1.46$  Mpc;  $h = 0.72$ ) with slope  $\gamma = 1.68 \pm 0.27$ , there is excellent agreement between results. Our measurement more cleanly removes the intrinsic C IV absorbers for a correct measurement of correlation, whereas [Wild et al. \(2008\)](#) modeled the intrinsic C IV absorbers and thus were reliant on more assumptions.

The clustering of C IV absorbers and Lyman Break Galaxies (LBGs) was measured in [Adelberger et al. \(2005\)](#) and [Cooke et al. \(2006\)](#) for CIV absorbers with rest-frame  $EW > 0.4\text{\AA}$ . [Adelberger et al. \(2005\)](#) measured the correlation length of CIV absorbers by comparing the LBG auto-correlation and LBG-CIV cross-correlation to be  $r_o \approx 5 \pm 1h^{-1}$  Mpc ( $7 \pm 1.4$  Mpc;  $h = 0.72$ ) at  $z \simeq 3$ . They also concluded that the C IV absorbers likely formed in these early large galaxies rather than in some more distributed environment. Our study from  $10 \text{ Mpc} < r_p < 100 \text{ Mpc}$  is  $1\sigma$  consistent with this result ( $r_o = 7.76 \pm 2.8$ ). Our study covers a much larger redshift range and has significantly greater statistical power due to the larger number of absorbers.

Our results corroborate the idea that LBG and C IV absorbers, having similar clustering properties, reside in similar environments and the same dark matter potentials.

## 2.7 SYSTEMATIC UNCERTAINTIES

In this section I discuss potential systematic uncertainties in our measurement presented in §2.6.

### 2.7.1 North Galactic Cap vs Full Sample

I explore a potential systematic difference between the North Galactic Cap (NGC) and South Galactic Cap (SGC) data set. The NGC portion of BOSS footprint is much larger than the SGC portion, which makes the correlation function for SGC alone very noisy. To explore

possible systematic effects I therefore compare the correlation function of the full sample with the NGC sample. The SGC's data quality is worse compared to the NGC for several reasons. First, the SGC suffers much more contamination from the Milky Way Galaxy compared to the NGC. Second, the SGC area is small ( $\sim 700 \text{ deg}^2$ ) and the footprint is not smoothly contiguous. This leads to an enhancement of any edge effects on the correlation function compared to the more contiguous coverage of the NGC ( $\sim 2600 \text{ deg}^2$ ). Third, our current understanding of other systematics is much better in the NGC than in the SGC area. All these issues with the SGC left us predisposed to expect that the DR9 NGC data is more reliable than the SGC data.

I present in Fig. 2.11 the three dimensional redshift space correlation function for the NGC. The bottom panel compares this correlation function to the correlation function of the full sample. A power-law fit for the correlation function finds a correlation length  $s_o = 9.26 \pm 1.23 \text{ Mpc}$  with slope  $\gamma = 2.06 \pm 0.25$  and a goodness-of-fit of  $\chi^2/\text{D.o.f} = 1.01$ . The correlation between the  $s_o$  and  $\gamma$  is 0.78. I also estimate, using the expression in Eq. 2.30, that  $\sqrt{b_{\text{qso}} b_{\text{CIV}}} = 2.05 \pm 0.46$ . Fig. 2.12 shows the projected correlation function of NGC sample. The bottom panel compares the projected correlation function to the projected correlation function of the full sample. I also fit the projected correlation function for  $r_0$  and  $\gamma$  from Eq. 2.19; I estimate  $r_0 = 7.75 \pm 1.04 \text{ Mpc}$  and  $\gamma = 1.84 \pm 0.09$  with a goodness-of-fit  $\chi^2/\text{D.o.f} = 1.25$ .

From Fig. 2.11 & 2.12 I see that the NGC correlation function is systematically lower than the full sample, which is also reflected in the estimation of  $\sqrt{b_{\text{qso}} b_{\text{CIV}}}$ . White et al. (2012) also find a noticeably larger auto-correlation for the quasars at these scales in the SGC. Despite the extensive search they were unable to find any systematics which would explain the discrepancy. The excess in the quasar auto-correlation would also cause an excess in the cross-correlation measurement. The difference in the NGC and SGC cross-correlation measurements are features of the data gathered to date. However, they are  $2\sigma$  consistent with each other. The sample size from the full BOSS, which will be about three times larger, will reveal whether this discrepancy is fundamental or a fluctuation.

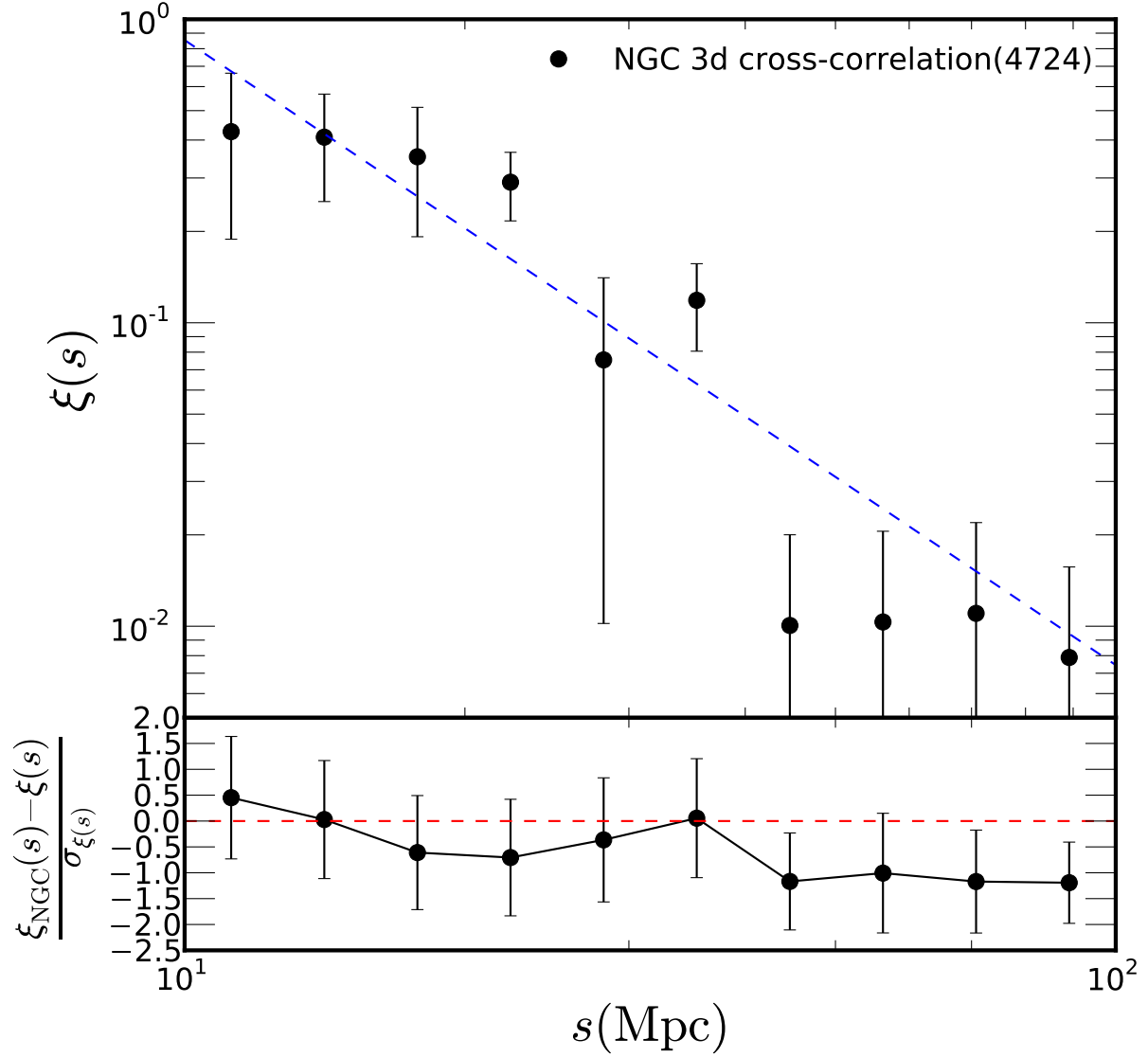


Figure 2.11 The redshift space correlation function of CIV absorbers and quasars in the NGC. The dotted line is the best fit power-law, as defined in Eq. 2.18, with  $s_o = 9.26 \pm 1.23$  Mpc and slope  $\gamma = 2.06 \pm 0.25$  in the range  $10 < s < 100$  Mpc. The redshift range for the C IV absorber and quasar is  $2.1 < z < 2.5$ . The lower panel compares the NGC correlation function to the full sample correlation function.

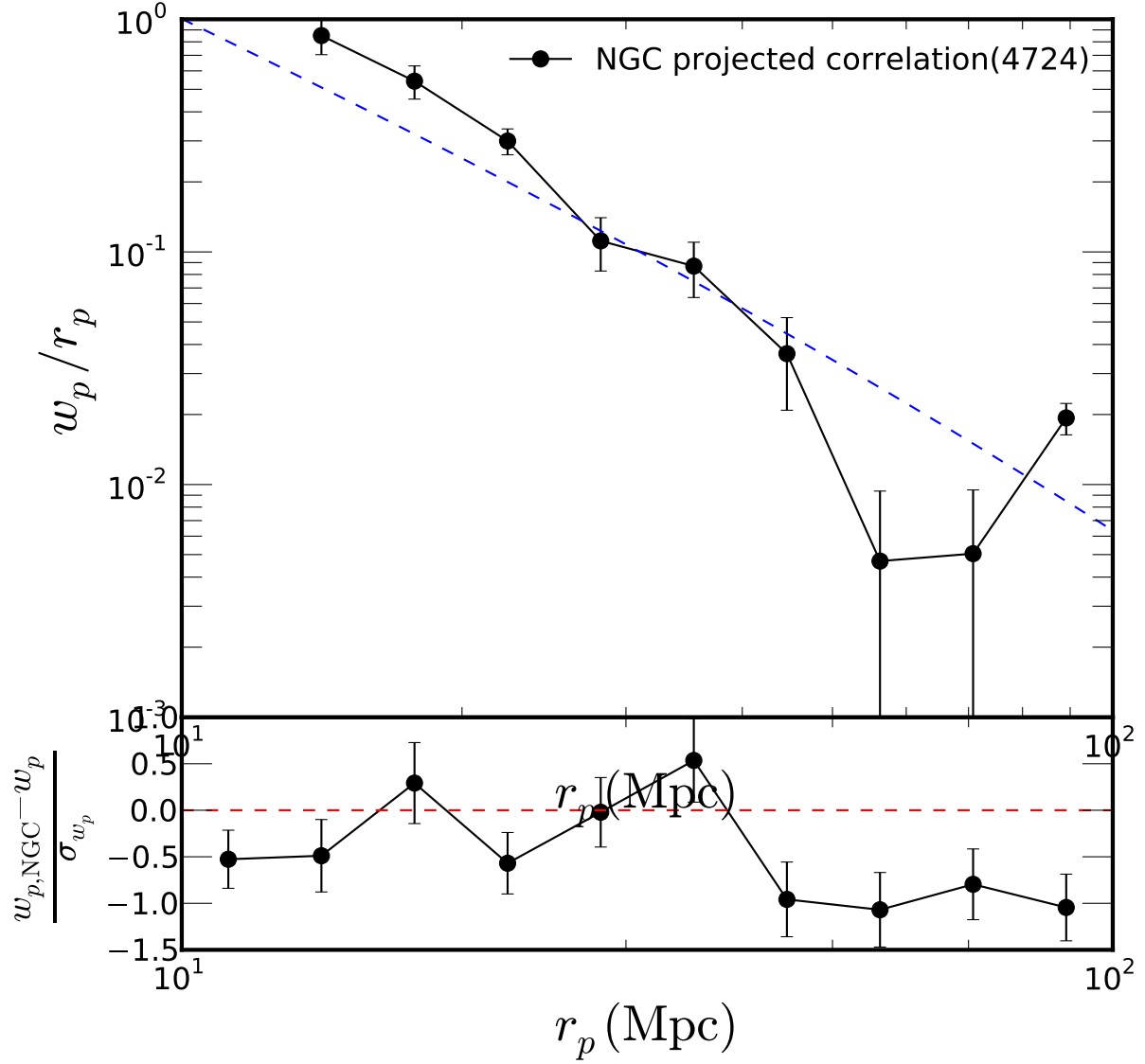


Figure 2.12 Projected correlation function for C IV absorbers and quasars in the NGC. The dashed line is the best fit power-law, as defined in Eq. 2.19 and 2.20, with  $r_0 = 7.76 \pm 3.80$  Mpc and slope  $\gamma = 1.74 \pm 0.21$  in the range  $10 \text{ Mpc} < w_p < 100 \text{ Mpc}$  in the redshift range of  $2.1 < z < 2.5$ . The lower panel compares the NGC projected correlation function to the full sample one.

### 2.7.2 CORE vs BONUS Systematics Error

I next explore potential systematic effects due to the survey configuration of having two separate samples of quasars: CORE and BONUS. Because our C IV absorbers are from both CORE and BONUS quasars, I investigate differences in clustering property of these two subsamples. Fig. 2.13 (top panel) shows the cross-correlation measurement of the CORE C IV absorbers and BONUS C IV absorbers. The BONUS sample has only 1818 absorbers; thus the error of the correlation function is relatively larger than for the CORE sample. It is therefore ineffective to compare the power-law fit of the two samples as the parameters are poorly constrained. As such I restrict our comparison to correlation function to determine if the two samples are consistent. The bottom panel of Fig. 2.13 shows the correlation function of CORE and BONUS in comparison to correlation function of the combined sample.

I estimate the  $\sqrt{b_{\text{QSO}}b_{\text{CIV}}}$  for CORE and BONUS to be  $2.56 \pm 0.44$  and  $3.80 \pm 0.71$ . Using the combined sample, the result,  $2.97 \pm 0.51$ , is within  $1\sigma$  for both CORE and BONUS. Therefore I conclude that there are no large systematic errors due to the targeting algorithm for source quasars. Any difference in the equivalent width distribution between CORE and BONUS is also not expected to be reflected in the systematics.

### 2.7.3 Measurement Robust Across Different BOSS Chunks

In this section I estimate the effect of the varying CORE algorithm in different chunks in the BOSS targeting process. Due to the changing targeting algorithm for the CORE sample in first year, there could be errors introduced by estimating larger completeness in one chunk compared to other chunks because the CORE target algorithm of a different chunk selected a different fraction of the target catalog generated by XDQSO algorithm. Within a chunk, the fractional difference in completeness determines the relative number of random points in those fields, and overall completeness only reflects in number density of the random points. In Fig. 2.14 I compare the overall correlation function measured with the average of the 19 correlation functions, each formed from individual chunks. The error for the case when the correlation measurement is done within a chunk is the Poisson error; the overall error is calculated by adding the errors from the different chunks in quadrature. The top panel

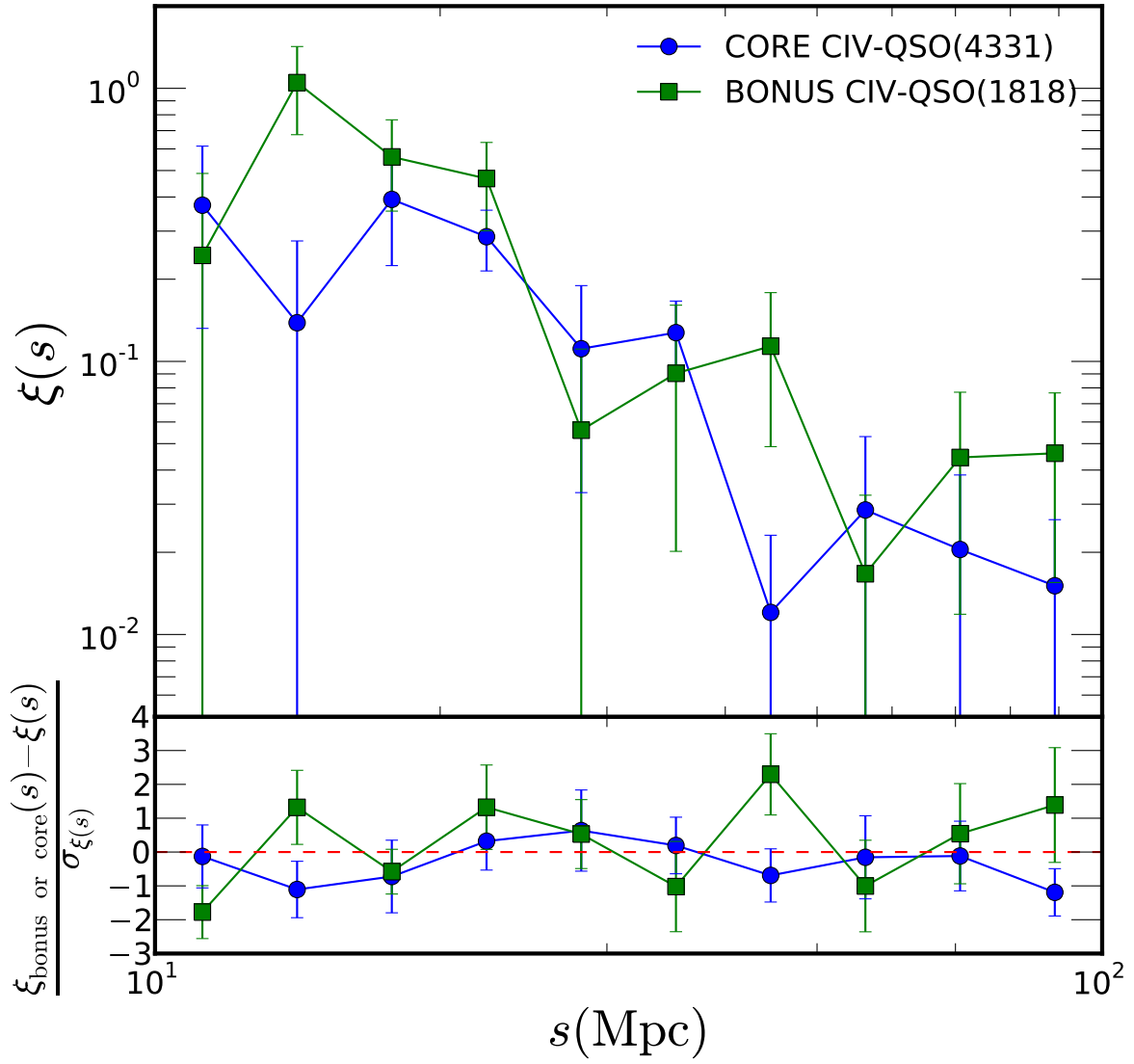


Figure 2.13 Cross-Correlation for the CORE CIV absorbers and BONUS CIV absorbers (top panel). The two correlation functions are consistent with each other, but the large errors would mask all but very large differences. The bottom panel compares the both sample correlation functions to the combined correlation function.

displays the correlation functions  $\xi_{\text{chunk}}(s)$  and  $\xi(s)$ . The bottom panel is the difference of the correlation calculated within chunk  $\xi_{\text{chunk}}$  and the overall correlation function in units of the Jackknife error of the overall correlation function. If there is a systematic error from the chunking process and evolving CORE algorithm, I would expect either consistently more than the correlation calculated within chunks or consistently less, caused by different overall levels of completeness, due to different algorithm used in different chunks. However, it is not clear the plot signifies any trend of the  $\xi_{\text{chunk}}$  being consistently either more or less than the overall estimate of correlation function, which indicates that there is no large effect from the use of slightly different selection algorithms in different BOSS chunks.

For the chunk correlation function I estimate  $\sqrt{b_{\text{qso}}b_{\text{CIV}}} = 2.07 \pm 0.61$  but the error is larger compared to combined sample. The correlation function does not appear to be biased compared to the combined sample. For the full BOSS sample the problem will be irrelevant as all subsequent chunks will use the same target selection algorithm. All the coverage will fill the space in the foot print and significantly reduce any edge effects.

#### 2.7.4 Other Systematic Errors

In this section I estimate the systematic effect of various properties of the sample on the estimates of the correlation strength ( $r_0$ ), the slope ( $\gamma$ ), and the bias of C IV absorbers and quasars  $\sqrt{b_{\text{CIV}}b_{\text{QSO}}}$ . The errors on our parameters are large, and the samples are not sufficiently large to perform the typical systematic analysis in which one calculates the correlation function for a bin for each parameter space and measure the change in the correlation function in every bin. Hence, I used a jackknife procedure because it works well on small samples. To estimate each systematic, I compared the Jackknife error caused by dividing the sample into bins based on a ordering in the given parameter to the Jackknife errors from a random division of the data in to same number of bins. The Jackknife error brings out the systematic error for the parameter in consideration. The significance of this is estimated by dividing the sample randomly and get the distribution of Jackknife error. Below is the specific procedure I follow:

1. Sort the C IV absorbers according to the given property (e.g., equivalent width).

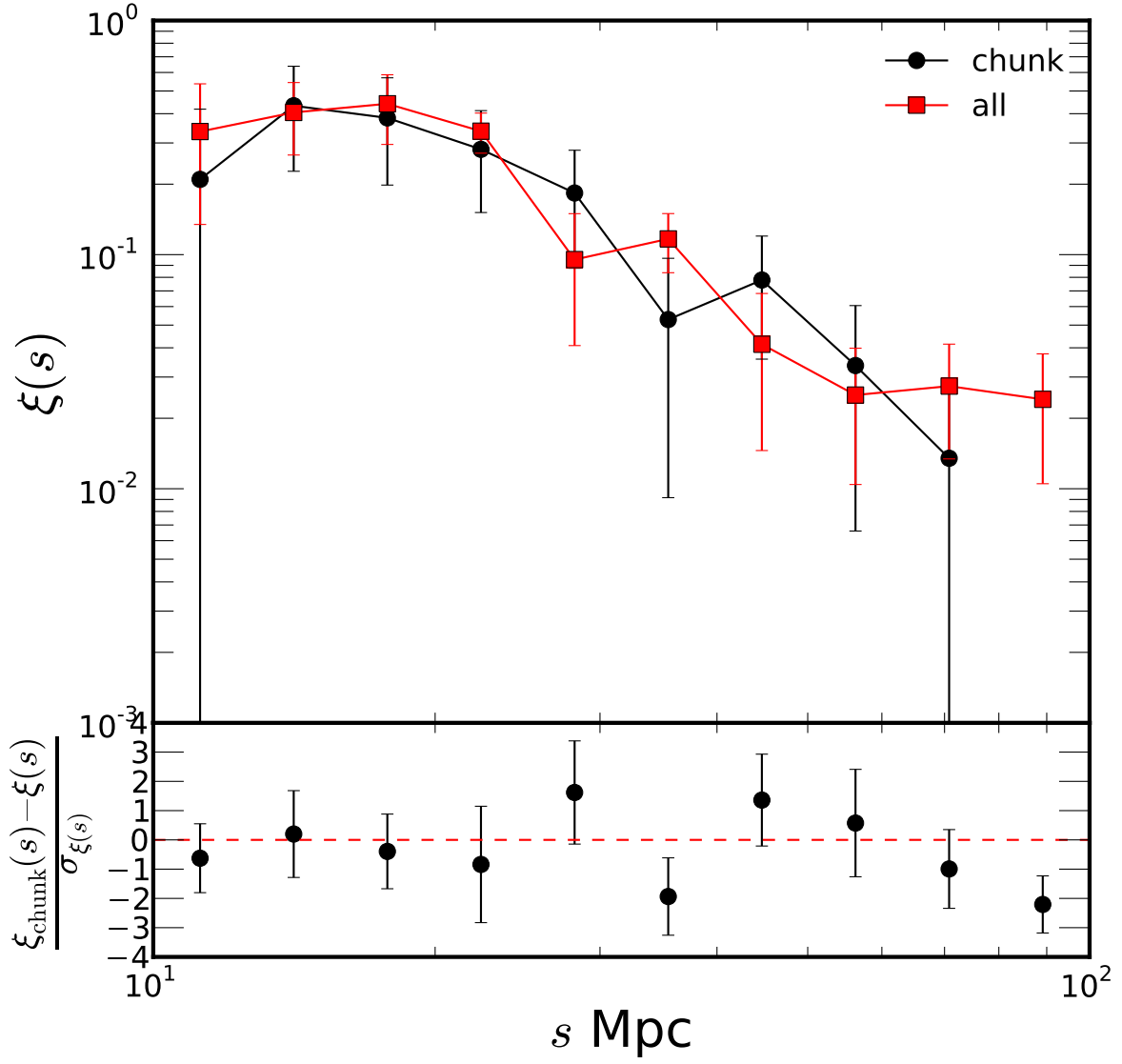


Figure 2.14 Top panel compares the average of cross-correlation functions calculated within chunks to the overall correlation function in the redshift distance range  $10 < s < 100$  Mpc. The bottom plot is the difference of the correlations function (in units of  $1\sigma$  Jackknife error) calculated for the overall correlation function. The plots indicate no significant systematic error for the correlation function caused by different algorithm used in different chunks and hence the overall completeness of chunks are appropriate.



2. Calculate the jackknife error by dividing the CIV absorber sample, according to property in consideration, into 10 bins for  $r_0$ ,  $\gamma$  and  $\sqrt{b_{\text{CIV}}b_{\text{QSO}}}$ .
3. Calculate the jackknife error by dividing the CIV absorber sample, randomly, into 10 bins for  $r_0$ ,  $\gamma$  and  $\sqrt{b_{\text{CIV}}b_{\text{QSO}}}$ .
4. Do the previous step 5,000 times and find the distribution of  $r_0$ ,  $\gamma$ , and  $\sqrt{b_{\text{CIV}}b_{\text{QSO}}}$ .
5. Estimate the probability of measured Jackknife error by random chance, called p-value by using of the distribution of the random scatter of errors in previous step.

Following the above procedure, I explore the systematic effects of absorber equivalent width,  $\beta$ ,  $i$ -band magnitude, absorber redshift, quasar spectroscopic features, and Galactic latitude. Table 2.4 summarizes the mean variation and standard deviation of the parameters for each systematic. Fig 2.15, 2.16, and 2.17 show the distribution of the parameters  $r_0$ ,  $\gamma$  and  $\sqrt{b_{\text{CIV}}b_{\text{QSO}}}$  from the random jackknifing of the sample. Below I describe each systematic and its potential effect on the correlation function measurements. In many cases a systematic error of one property could be correlated with that of another.

1. **Absorber Equivalent Width:** There are two obvious ways the equivalent width of the CIV absorber could affect the systematic error.

A) There could be a few false positive CIV absorbers in the sample, and such contamination may not be distributed uniformly across the equivalent width distribution. The lower equivalent width absorbers are more likely to be contaminated by false positives compared to the high equivalent absorbers. This contamination will decrease the correlation strength for lower equivalent width absorbers.

B) There could also be an intrinsic correlation dependence on equivalent-width. The higher equivalent-width absorbers could be more correlated with dark matter compared to lower equivalent-width absorbers. However, our error estimations of the correlation function are not small enough to measure this trend.

Following our systematic analysis, I found a noticeable, but not statistically significant, increase in the change in bias as different equivalent-width bins are dropped. The probability of having such error occurring by chance is 13%.

2.  $\beta$ : The CIV absorber sample could have two basic origins. One may be intrinsic to quasars

and quasar host galaxies, the other to intervening material in inter-galactic space. These two samples will have different clustering properties. I remove a large sample of intrinsic C IV absorbers by having a minimum cut on the relative absorber velocity with respect to the quasar,  $\beta$ . However, I can expect some remaining contamination of the intrinsic C IV absorber in our sample (see Figure 2.4). This contamination would be distributed asymmetrically in  $\beta$  because lower values of  $\beta$  are more likely to be contaminated by intrinsic C IV absorbers than higher  $\beta$ . This systematic would, therefore, overestimate the effect of contamination on  $r_0$ ,  $\gamma$  and  $\sqrt{b_{\text{CIV}}b_{\text{QSO}}}$ .

I find that the systematic error due to  $\beta$  is marginally significant for the bias (Table 2.7.4) and quite significant for  $r_0$  and  $\gamma$ . I conclude that there is a non-trivial number of intrinsic C IV absorbers in our sample. I determine the error due to the  $\beta$  systematic alone as about  $\sim 2.8$  Mpc in  $r_0$  and  $\sim 0.28$  in  $\gamma$ . The strong effect on  $r_0$  and  $\gamma$  but weaker effect on the bias can be explained if the intrinsic C IV affects the correlation function at small scales only (bias is determined from a volume-weighted average).

This result motivates future work to better understand the intrinsic absorber population around quasars.

3. ***i*-band Magnitude:** There are two ways the apparent *i*-band magnitude can affect the correlation function systematically.

A) False-positive C IV absorbers are more likely to occur in the spectrum of a fainter quasar than a brighter one. A false-positive signal randomly distributed would dilute any inherent clustering in the sample. Therefore absorbers found against fainter quasars could produce systematically lower clustering strength than those found against brighter ones.

B) The *i*-band magnitude could affect the correlation because brighter apparent magnitudes quasars are more likely to be brighter in absolute magnitude (because of the restricted redshift range) and thus likely to be in a more highly clustered environment, assuming brighter quasars reside in more massive halos. Thus some of the intervening C IV absorbers are likely to be from clustered environment of the host galaxy.

I estimate this systematic error with *i*-band magnitude to be not very significant (Table 2.7.4). The systematic effect are at the  $1\sigma$  of the mean random expectation of error

and the p-value similarly indicates no significant deviation from random chance.

4. **Absorber Redshift:** The potential systematic effect of contamination because of false positives due to potential incomplete sky subtraction in the BOSS quasar spectra is minimal in this analysis. A sky line at a particular wavelength would affect the C IV absorbers at a particular absorber redshift. Any sky line which falls in the observed wavelength range for a given redshift range for C IV absorbers could contribute to a reduced signal in this range. Such contamination would possibly lead to smaller clustering measurement which would lead to systematic error. However, the strong O I sky line 5570-5590Å is removed from the absorber pipeline, which corresponds to C IV absorber redshift of 2.59. Our cutoff absorber redshift of 2.5 avoids any neighboring part of spectrum which might be affected.

With this motivation in mind for potential lines I may have neglected in the above cut, I searched for a dependence of our fit parameters on the absorber redshift. However, I found no significant systematic effect (Table 2.7.4). Hence I expect that the sky subtraction for the relevant region of the spectrum is sufficient and no sky-line-contamination creates false C IV absorber detections.

5. **Galactic Latitude:** The extinction through the Milky Way varies with galactic latitude. Such extinction could be correlated to poor signal-to-noise and could lead to false positive detection of C IV absorbers. The Galactic latitude could also potentially interact with the cosmic variance error along with contamination effect on correlation function. Hence the estimate of error could be overestimating error because of contamination.

Table 2.7.4 shows the significance of the systematic error due to Galactic latitude in bias. This is another way of looking at the NGC vs. SGC discrepancy discussed in 2.7.1. I estimate the error due to Galactic latitude on  $\sqrt{b_{\text{CIV}}b_{\text{QSO}}}$  to be 0.494 with  $< 3\%$  probability of such a shift occurring by chance.

6. **Quasar Redshift:** The biggest potential systematic from quasars at different redshifts (beyond any apparent magnitude variation as explored above) is a potential systematic contamination associated with features in the quasar spectrum, which could lead to a false positive identification as a C IV absorber. These contaminating lines would affect the correlation function asymmetrically at different rest frame wavelengths. However,

Table 2.3. Systematic error estimates and p-values for  $r_0$ ,  $\gamma$  and  $\sqrt{b_{\text{CIV}}b_{\text{QSO}}}$ .

Description	$\delta r_0$	$\delta \gamma$	$\delta \sqrt{b_{\text{CIV}}b_{\text{QSO}}}$
Equivalent Width	2.562	0.306(0.424)	0.477(0.130)
$\beta$	3.875(0.027)	0.405(0.051)	0.424(0.298)
i-band Magnitude	3.344(0.140)	0.335(0.266)	0.351
Absorber Redshift	2.574	0.258	0.412(0.346)
Galactic Latitude	3.300(0.157)	0.335(0.270)	0.618(0.003)
Quasar rest frame $\lambda$ <sup>a</sup>	3.874(0.027)	0.404(0.052)	0.415(0.331)

<sup>a</sup>The absorber redshift,  $\beta$ , and quasar rest frame are three different representations of only two independent quantities.

this systematic error actually becomes strongly correlated with the  $\beta$  systematic error because the absorbers that are near particular quasar rest-frame wavelengths also fall into specific  $\beta$  range. I indeed find very similar dependence between  $\beta$  and the quasar redshift as shown in Table 2.7.4.

Table 2.4 Random error distribution for  $r_0$ ,  $\gamma$  and  $\sqrt{b_{\text{CIV}}b_{\text{QSO}}}$ .

Parameter	mean	std dev
$\delta r_0$	2.667	0.628
$\delta \gamma$	0.293	0.068
$\delta \sqrt{b_{\text{CIV}}b_{\text{QSO}}}$	0.376	0.089

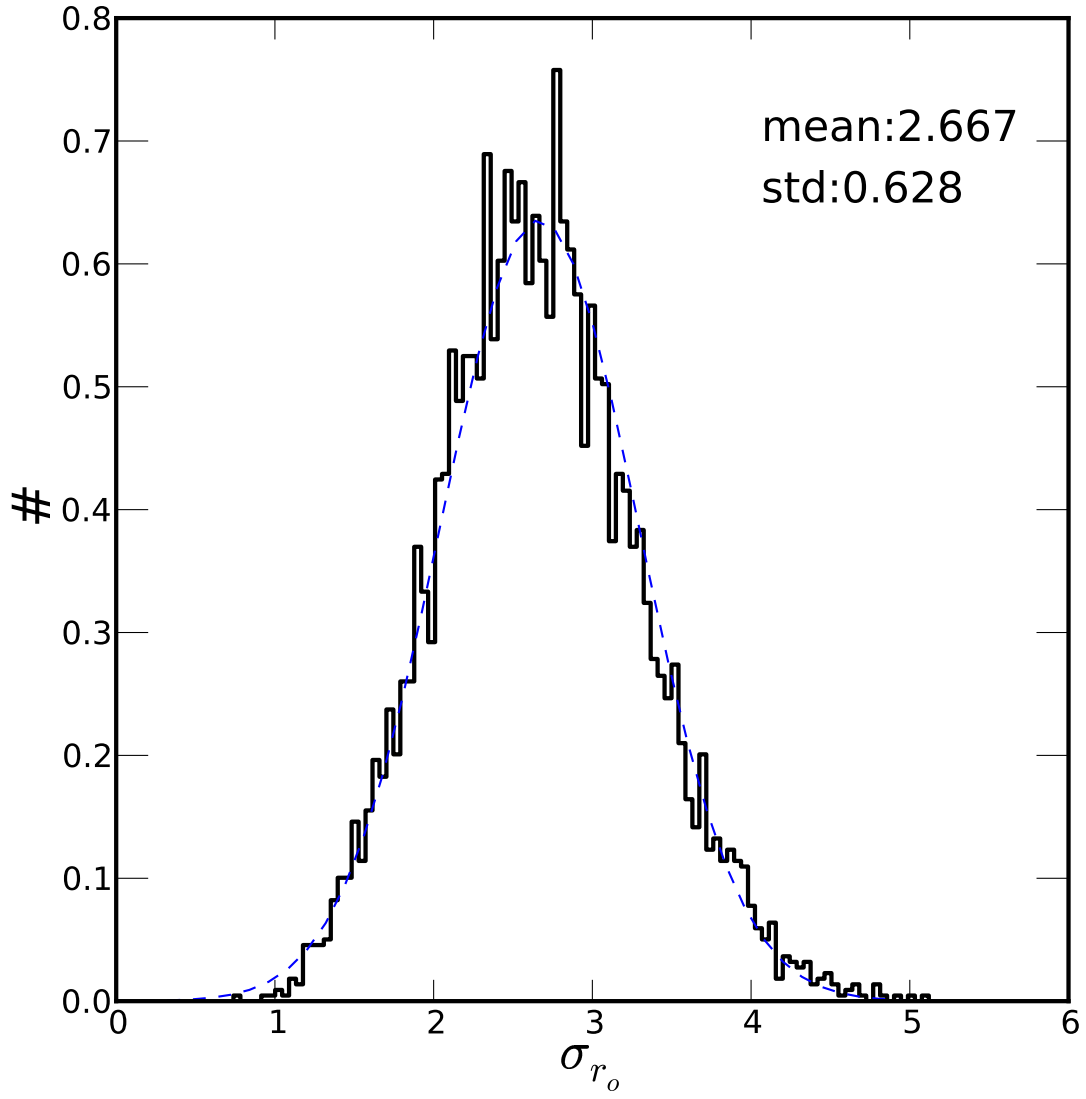


Figure 2.15 Error distribution for  $r_0$  [Mpc] from 5000 binned jackknife resamplings of the absorber sample. The distribution can be well approximated as Gaussian (dashed blue line).

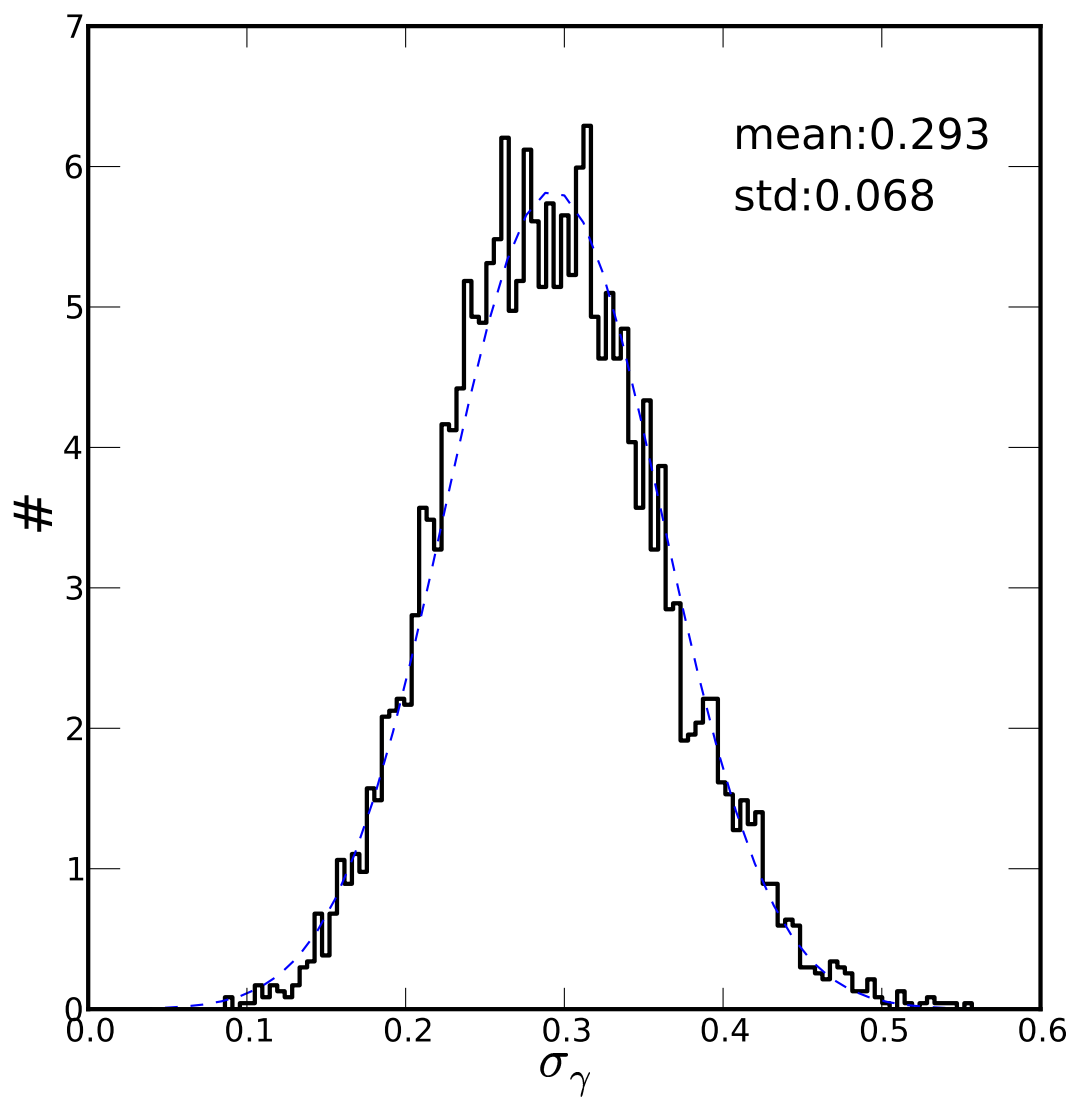


Figure 2.16 Error distribution for  $\gamma$  from 5000 binned jackknife resamplings of the absorber sample. The distribution can be well approximated as Gaussian (dashed blue line).

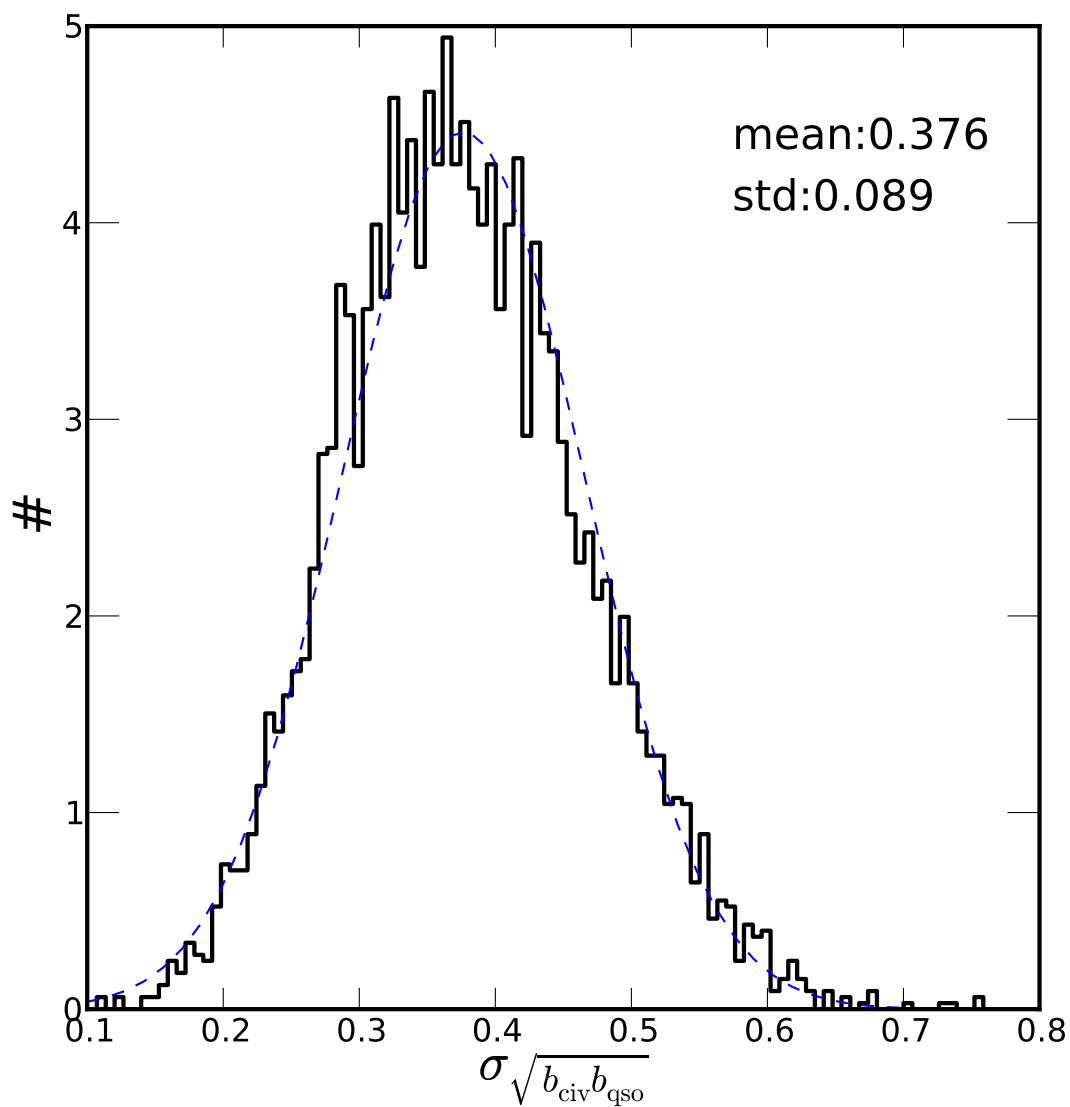


Figure 2.17 Error distribution for  $\sqrt{b_{\text{CIV}} b_{\text{QSO}}}$  from 5000 binned jackknife resamplings of the absorber sample. The distribution can be well approximated as Gaussian (dashed blue line).

## 2.8 SUMMARY AND FUTURE DIRECTIONS

This study has measured the correlation strength of C IV absorbers with the quasars from the BOSS survey. I focus on correlations between  $10 \text{ Mpc} < s < 100 \text{ Mpc}$  at  $z \sim 2.3$ , probing the large-scale clustering unaffected by details of the astrophysics of the galaxy environment surrounding quasars. I conclude the following:

- The three-dimensional two-point cross-correlation for C IV absorbers and quasars is well approximated by a power law in the distance range  $10 < s < 100 \text{ Mpc}$  with  $s_0 = 8.46 \pm 1.46 \text{ Mpc}$  and  $\gamma = 1.68 \pm 0.27$ .
- The projected cross-correlation for C IV absorbers and quasars is well approximated by a power law in the distance range  $10 < r_p < 100 \text{ Mpc}$  with  $r_0 = 7.76 \pm 3.80 \text{ Mpc}$  and  $\gamma = 1.74 \pm 0.21$ .
- I measure the combined QSO-C IV absorber bias  $\sqrt{b_{\text{qso}} b_{\text{CIV}}} = 2.97 \pm 0.51$ .
- I estimate the quasar auto-correlation and find a correlation length  $s_o = 12.19 \pm 0.32 \text{ Mpc}$  and slope  $\gamma = 1.77 \pm 0.04$  and thus infer a quasar bias of  $b_{\text{qso}} = 3.71$ .
- Using this estimate of the quasar bias  $b_{\text{qso}}$  I find  $b_{\text{CIV}} = 2.38 \pm 0.82$  and that  $\text{EW} > 0.28 \text{ \AA}$  C IV absorbers reside in halos of mass  $M_{\text{CIV}} \geq 10^{12} M_{\odot}$ .
- The dominant sources of systematic error in our estimation of C IV absorber bias are (1) a difference as a function Galactic latitude (NGC vs. SGC; §2.7.1); (2) absorber equivalent width; and (3) potential contamination of high-velocity intrinsic-absorbers ( $\beta > 0.2$ ).

This study lays the groundwork for subsequent work of both improved clustering analysis with an extended data set, as well as enabling complementary approaches to investigate C IV absorbers. With the well-constrained correlation of C IV absorbers at cosmological separations, one can propagate the two-halo correlation function down to small scales to remove this contribution from low- $\beta$  absorbers, enabling a cleaner investigation of C IV absorbers in the same halo as the quasars. Any departure from the expected number of C IV absorbers in the same halo as the quasars. Any departure from the expected number of C IV absorbers would indicate the role of quasars in creating/destroying the absorbers, leading to a better understanding of quasars.



A repeated analysis with the full BOSS sample will not only have  $\sim 3$  times more quasars and absorbers, but will also have significantly reduced edge effects and have a more uniform completeness and coverage. The question of any NGC vs. SGC difference (currently consistent with Poisson fluctuations) will be settled, and with a cleaner sample of quasars and absorbers it will be possible to make a random catalog for CIV absorbers without having to assume a specific redshift dependence of their number density. The increased number of absorbers will also allow us to measure the correlation function as a function of equivalent width and other absorber properties. The final SDSS-III BOSS C IV absorber analysis will feature improved systematic errors and more clearly highlight the statistical power of these large samples.

### 3.0 QUASAR OUTFLOWS USING INTRINSIC ABSORPTION SYSTEMS

In §1.3 I presented an overview of quasars and their utility. I introduced the idea of using absorption systems to study the structure of quasars. In this chapter, I study the outflows in quasars using C IV absorbers seen in the spectra of SDSS-III BOSS quasars from DR9. In §3.1, I describe the motivation behind, and the importance of, this study. In §3.2, I present the models for the data and explain the reasoning behind them. In §3.3, I explain the halo occupation formalism, which is used as the guiding principle for the estimation of the correlation function. In §3.4, I present the observational data used for this study. In §3.5, I explain the estimation of the correlation function required for the models. In §3.6, I present the result of the analysis and interpretation. In the last section, §3.7, I present a summary of this analysis and comment on future directions for this study.

#### 3.1 MOTIVATION

Quasars can be identified during the epoch when galaxies were assembling and the star formation rate was ten times higher than today. Because they are a biased tracer of high density environments in the early universe, understanding quasars can help in understanding the formation of large scale structure and the formation and evolution of galaxies. Being very energetic, quasars can be powerful engines that mix material within a galaxy as well as expell material into the Inter Galactic Medium (IGM). Such feedback processes have been postulated to reduce the growth of baryonic structure in the early universe (Silk and Rees 1998; Springel et al. 2005; Di Matteo et al. 2005; Bower et al. 2006). Therefore understanding quasars and their outflows is an important route to correctly explain the formation of

stars and the distribution of elements in and around galaxies.

Many models of quasar outflows postulate that the gas arises from the accretion disk. But we still do not know how these flows are launched. There have been many models explaining their origin and how they are ejected from the inner region. Some models use only line radiation pressure (Arav et al. 1994; Murray et al. 1995; Proga et al. 2000) while others add in magnetic forces (de Kool and Begelman 1995; Everett 2005; Proga and Kallman 2004) to accelerate the material.

Despite their importance, the understanding of quasars is fairly limited due to their extreme distance and extreme physics. Many studies have been done to understand quasar outflows from the broad absorption lines (BALs) (e.g., Weymann et al. 1979; Yuan and Wills 2003; Richards 2006; Ganguly et al. 2007; Lundgren et al. 2007). The BALs are unambiguously associated with quasars which make them easy targets for detailed study. There have been other studies using narrow absorption lines (NALs) to study the outflows of quasars (Foltz et al. 1988; Aldcroft et al. 1994; Ganguly et al. 2001; Baker et al. 2002; Vestergaard 2003; Richards 2001; Misawa et al. 2007; Ganguly et al. 2007). The study of NALs has many advantage over BALs. Most notably the NALs are detected in a large fraction of quasars ( $\sim 50\%$ ) compared to BALs ( $\sim 10\%$ ). And unlike BALs, NALs do not suffer from line blending.

However NALs do suffer from one important disadvantage: NALs are produced by the intervening galaxies along the line of sight as well. Hence identifying the NAL to be intrinsic to the quasar is often a very difficult task. However a large fraction of the NALs having a redshift similar to the quasar redshift are likely intrinsic. But these can still have significant velocities with respect to the quasar. For example, Richards (2001) suggests that  $\sim 36\%$  of NALs with a velocity with respect to the quasar rest frame of  $v > 5000$  km/s are intrinsic, i.e., physically close in distance to the quasar.

NALs also provide a complementary study of quasars compared to BALs. As the BAL gas clouds are believed to be closer to the accretion disk and NAL gas clouds are much further, they probe different parts of a quasar and together, may offer a more complete picture of the quasar and the surrounding environment.

### 3.2 NUMBER DENSITY OF C IV ABSORBERS

The light from a quasar travels through its own dark matter halo and other halos picking up signatures of the absorption systems encountered. The frequency of such encounters is determined by the number density of the absorption systems. Figure 3.1 shows a schematic diagram of a sample line of sight from a quasar to an observer. In this section I model the observed frequency of absorption systems detected in the rest-frame of the backlighting quasars. Motivated by the different physical origins of the absorption systems, I divide the absorbers into three broad categories: 1. in the host halo due to clustering (one halo); 2. in an intervening halo (two halo); 3. in the outflowing gas due to quasar environment (outflow).

The total probability of an absorption system can now be written as

$$dP = dP^{1h} + dP^{2h} + dP^{\text{outflow}} \quad (3.1)$$

I use separate models for describing each separate component.

- **Two-halo  $dP$ :** We are going to first evaluate the  $dP^{2h}$  term. For this component the absorption systems are not very close to the quasar in velocity space. In the pencil beam survey the probability of detecting an absorber between  $z$  and  $z + dz$  is given as (e.g., [Hogg 1999](#))

$$dP^{2h} = n(z)\sigma(z) \frac{c}{H_o} \frac{(1+z)^2}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}} dz \quad (3.2)$$

where  $n(z)$  and  $\sigma(z)$  are the number density and cross section respectively of C IV absorbers at redshift  $z$ .  $\Omega_M$ ,  $\Omega_\Lambda$ ,  $H_o$  are the relevant cosmological parameters. Modeling the redshift dependence of  $n(z)$  as a correlation of quasars and C IV absorbers we can write

$$n(z)\sigma(z) = n_o\sigma_o(1 + \xi^{2h}(r; z_{\text{qso}}))(1+z)^\epsilon \quad (3.3)$$

where  $\epsilon$  characterizes the evolution of number density with redshift and  $n_o\sigma_o$  is the current value of number density and cross-section.  $\xi^{2h}(r; z_{\text{qso}})$  is the cross-correlation function of quasars and C IV absorbers from different halos. Note that the  $\xi$  in the equation indicates that matter in the universe is clustered and hence, even with no

intrinsic physical connection, there are more C IV absorbers near quasars compared to further away.

Since we are interested in outflow velocities from the quasar, it is logical to do the analysis in the velocity space of the quasar rest-frame. I convert probabilities in redshift space to probabilities in quasar rest-frame velocity space,  $\beta$ , using the following relationships

$$\beta \equiv \frac{v}{c} = \frac{(1 + z_{\text{qso}})^2 - (1 + z)^2}{(1 + z_{\text{qso}})^2 + (1 + z)^2} \quad (3.4)$$

and

$$d\beta \equiv \frac{dv}{c} = -\frac{4(1+z)(1+z_{\text{qso}})^2 dz}{[(1+z_{\text{qso}})^2 + (1+z)^2]^2}. \quad (3.5)$$

This leads to an expected probability of C IV absorbers from intervening DM halos of

$$\frac{dP^{2h}}{d\beta}(z_{\text{qso}}) = n_o \sigma_o (1 + \xi^{2h}(r; z_{\text{qso}})) \frac{c}{hH_o} \frac{(1+z)^{1+\epsilon}}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \frac{[(1+z_{\text{qso}})^2 + (1+z)^2]^2}{4(1+z_{\text{qso}})^2} \quad (3.6)$$

- **One-halo dP:** For the single halo term I assume that the host halo is virialized. So the velocity of an absorption system in the rest-frame of quasar can be well approximated as a Gaussian

$$p(v) dv = \frac{1}{\sqrt{2\pi\sigma_v^2}} \exp\left(-\frac{v^2}{2\sigma_v^2}\right). \quad (3.7)$$

Hence, for the single halo term we can write the probability of observation as

$$\frac{dP^{1h}}{d\beta}(z_{\text{qso}}) = \frac{f}{\sqrt{2\pi}} \exp\left(-\frac{\beta^2}{2\sigma_\beta^2}\right) (1 + z_{\text{qso}})^\epsilon \quad (3.8)$$

Here we assume that the average number of absorbers in a halo evolves as  $(1 + z_{\text{qso}})^\epsilon$ .

The parameters unknown in the above equation are  $f$ ,  $\sigma_\beta$ .

- **Outflow dP:** The outflow term is modeled as a piece-wise continuous function described by

$$\frac{dP^{\text{outflow}}}{dv} = \begin{cases} n_{2k}/2000 & 0 < v < 2000 \text{ km/s} \\ (n_{4k} - n_{2k})/2000 & 2000 < v < 4000 \text{ km/s} \\ (n_{6k} - n_{4k})/2000 & 4000 < v < 6000 \text{ km/s} \\ -n_{6k}/2000 & 6000 < v < 8000 \text{ km/s} \\ 0 & v < 0 \text{ km/s} \& v > 8000 \text{ km/s} \end{cases} \quad (3.9)$$

The simple piece-wise function is considered appropriate as it makes the fewest assumptions about the shape of the outflow distribution while at the same time having only a small number of free parameters. The velocity range of the function is chosen to be 0-8000 km/s because in tests of this range any free parameter greater than 8000 km/s was found to be consistent with zero.

In the SDSS-III BOSS DR9 sample the redshift of the quasar,  $z_{\text{qso}}$ , is uncertain due to the astrophysical variation of different emission line velocities. Hence the measured value of the number of absorbers in a bin between  $r$  and  $r + dr$  will be a convolution of the redshift error of the quasar with the actual number density of absorbers. We can not observe absorption lines at all possible redshifts; we can only observe the absorbers that are physically between us and the quasars. Also, a quasar spectrum observed from the ground can only detect CIV absorption redward of the UV. Therefore, for every quasar at redshift  $z_{\text{qso}}$  there is a minimum  $z_{\text{min}}(z_{\text{qso}})$  and maximum redshift  $z_{\text{max}}(z_{\text{qso}})$  at which we can observe a CIV absorption system in the SDSS-III BOSS data.

Hence the observed number density from all quasars can be given as

$$\left. \frac{dP}{d\beta} \right|_{\text{observable}} = \text{Gaussian}(0, \sigma_z) * \sum_{\text{qso}} \frac{dP}{d\beta}(z_{\text{qso}}) H(z - z_{\text{min}}(z_{\text{qso}})) H(z_{\text{max}}(z_{\text{qso}}) - z) \quad (3.10)$$

where  $H$ ,  $z_{\text{max}}$ , and  $z_{\text{min}}$  are the Heaviside Step Function, maximum redshift, and minimum redshift respectively.

### 3.3 CORRELATION FUNCTIONS IN A HALO MODEL FRAMEWORK

Halo models are a formalism to describe the clustering of objects. The formalism has a long history and has provided important analytical descriptions of large scale clustering (Neyman and Scott 1952; McClelland and Silk 1977a,b; Peebles 1974). After the realization that most matter in the universe is in the form of dark matter which interacts only gravitationally, the halo formalism was further developed to provide an analytical tool for predicting clustering of dark matter halos (Mo and White 1996; Sheth and Tormen 1999; Sheth et al.

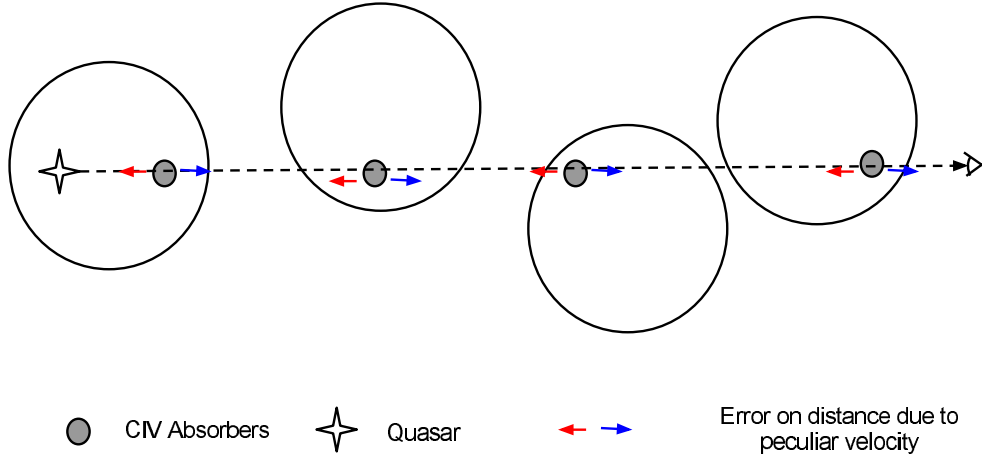


Figure 3.1 A cartoon description of a line of sight from a quasar (left) to an observer (right). The big circles indicate the dark matter halos. The arrows shows the uncertainty in location due to peculiar velocities within the host halos.

2001; Seljak and Warren 2004; Tinker et al. 2005). These models developed for dark matter halos are easily extensible for studies of the clustering of any population.

### 3.3.1 Basics of The Halo Model Formalism

The halo model formalism is based on a few assumptions. One of the basic assumptions is that all matter resides in halos of different sizes. The size distribution of halos is given by the mass function, denoted by  $dn/dM$  (e.g., Sheth and Tormen (1999); Jenkins et al. (2001)). The mass function is the number of dark matter halos of mass between  $M$  and  $M + dM$  in a comoving unit volume. The halo bias is  $b_h(M)$  is defined as the overdensity of halo of mass between  $M$  and  $M + dM$  compared to the overdensity of all matter (Efstathiou et al. 1988; Mo and White 1996; Jing 1998; Sheth and Tormen 1999). The distribution of dark matter within a halo is described by the density profile around the center of the halo as  $\lambda(r|M)$  (Navarro et al. 1997; Bullock et al. 2001a). These ingredients are estimated using dark matter simulations or approximate analytical solutions.

Using the ingredients of the halo model formalism we can calculate the clustering of

any kind of object or of different types of objects. Here I estimate the two-point correlation function of CIV absorbers and quasars using the halo model formalism below. The two-point correlation function describes the clustering of C IV absorber and quasar pairs as a function of the distance between them. Any pair of CIV absorber and a quasar can be of either of two origins; 1) both reside in the same halo, called the one-halo term or, 2) reside in different halo, called the two-halo term. The total correlation function is the sum of these two and can be written as follows.

$$\xi_{\text{qso,CIV}}(r) = \xi_{\text{qso,CIV}}^{1h}(r) + \xi_{\text{qso,CIV}}^{2h}(r) \quad (3.11)$$

where  $\xi_{\text{qso,CIV}}^{1h}(r)$  is the one-halo correlation term and  $\xi_{\text{qso,CIV}}^{2h}(r)$  is the two-halo term. These two terms can be calculated separately (Scherrer and Bertschinger 1991). The one halo term is written as

$$\xi_{\text{qso,CIV}}^{1h}(r) = \bar{n}_{\text{qso}}^{-1} \bar{n}_{\text{CIV}}^{-1} \int dM \frac{dn}{dM} \langle N_{\text{qso}} N_{\text{CIV}} \rangle(M) \int d^3 \vec{x} \lambda(\vec{x}|M) \lambda(\vec{x} + \vec{r}|M). \quad (3.12)$$

where  $\bar{n}_{\text{qso}}$  and  $\bar{n}_{\text{CIV}}$  are the average number density of quasars and C IV absorbers, respectively.  $\langle N_{\text{qso}} N_{\text{CIV}} \rangle(M)$  is the average of the number of quasars times the number of C IV absorbers in halos of mass between  $M$  and  $M + dM$ .

Similarly, the two-halo term can be written as follows.

$$\begin{aligned} \xi_{\text{qso,CIV}}^{2h}(r) = & \bar{n}_{\text{qso}}^{-1} \bar{n}_{\text{CIV}}^{-1} \int dM \frac{dn}{dM} \langle N_{\text{qso}} \rangle(M) \int dM' \frac{dn}{dM'} \langle N_{\text{CIV}} \rangle(M') \\ & \times \int d^3 \vec{x} \int d^3 \vec{y} \lambda(\vec{x}|M) \lambda(\vec{y}|M') \xi_{\text{hh}}(\vec{x} - \vec{y} - \vec{r}|M, M') \end{aligned} \quad (3.13)$$

where  $\langle N_{\text{qso}} \rangle(M)$  and  $\langle N_{\text{CIV}} \rangle(M)$  are the average number of quasars and C IV absorbers respectively, in the halos of mass between  $M$  and  $M + dM$ , and  $\xi_{\text{hh}}(M, M')$  is the two-point cross-correlation function of dark matter halos of mass  $M$  with those of mass  $M'$ .

For our analysis we will be required to calculate only  $\xi_{\text{qso,CIV}}^{2h}(r)$  and not  $\xi_{\text{qso,CIV}}^{1h}(r)$ . The two halo term can further be simplified by assuming  $\xi_{\text{hh}}(r|M, M') \simeq b_h(M) b_h(M') \xi_{DM}^{\text{lin}}(r)$ ,



where  $\xi_{DM}^{\text{lin}}$  is the dark matter power spectrum in linear perturbation theory. Using this assumption the two-halo cross-correlation function can be written as

$$\begin{aligned} \xi_{\text{qso,CIV}}^{2h}(r) &= \bar{n}_{\text{qso}}^{-1} \bar{n}_{\text{CIV}}^{-1} \int dM \frac{dn}{dM} \langle N_{\text{qso}} \rangle(M) b_h(M) \int dM' \frac{dn}{dM'} \langle N_{\text{CIV}} \rangle(M') b_h(M') \\ &\times \int d^3 \vec{x} \int d^3 \vec{y} \lambda(\vec{x}|M) \lambda(\vec{y}|M') \xi_{\text{DM}}^{\text{lin}}(\vec{x} - \vec{y} - \vec{r}|M, M') \end{aligned} \quad (3.14)$$

It is often helpful to take the Fourier transform of an equation that involves convolution as the convolution in real space become simple multiplication in Fourier space. We can write the above equation in Fourier space as follows.

$$\begin{aligned} P_{\text{qso,CIV}}^{2h}(k) &= \bar{n}_{\text{qso}}^{-1} \bar{n}_{\text{CIV}}^{-1} P^{\text{lin}}(k) \int dM \frac{dn}{dM} \langle N_{\text{qso}} \rangle(M) \lambda(k|M) \\ &\times \int dM' \frac{dn}{dM'} \langle N_{\text{CIV}} \rangle(M') \lambda(k|M') \end{aligned} \quad (3.15)$$

where  $\bar{n}$  is defined as

$$\bar{n} = \int dM \frac{dn}{dM} \langle N \rangle \quad (3.16)$$

### 3.3.2 Mass Function and Bias

The equations in the halo model formalism are generally written in term of the variable  $\nu \equiv \delta_c(z)/\sigma(M)$ , where  $\delta_c(z)$  is the equivalent linear collapse overdensity and  $\sigma(M)$  is the rms mass fraction in the linear density field smoothed on a scale containing mass  $M$ . The quantity  $f(\nu) d\nu$  denotes the fraction of mass contained in halos in a range  $d\nu$  about  $\nu$ . Then the mass function is related to  $f(\nu)$  by

$$\frac{dn}{dM} = 2\nu^2 f(\nu) \left( \frac{\bar{\rho}}{M} \right) \frac{d \ln \nu}{dM}. \quad (3.17)$$

Using the above equation we can write

$$P_{\text{qso,CIV}}^{2h}(k) = P^{\text{lin}}(k) b_{\text{qso}}(k) b_{\text{CIV}}(k), \quad (3.18)$$

where  $b(k)$  can be written as

$$b(k) = \frac{\int d \ln(\nu) \nu^2 f(\nu) b_h(\nu) \lambda(k|\nu) \langle N \rangle(M)}{\int d \ln(\nu) \nu^2 f(\nu) \langle N \rangle(M)}. \quad (3.19)$$

There are many different mass functions which are derived from analytical and dark matter simulations (Press and Schechter 1974; Sheth et al. 2001; Jenkins et al. 2001; Tinker et al. 2010). Here we use the mass function and halo bias from Sheth et al. (2001) which is based on a model of ellipsoidal collapse of dark matter. The mass function of Sheth-Tormen is given by

$$f(\nu) = A(p) \sqrt{\frac{2a}{\pi}} \left( 1 + \frac{1}{(\sqrt{a}\nu)^{2p}} \right) \nu \exp(-a\nu^2/2) \quad (3.20)$$

where  $a = 0.707$ ,  $p = 0.3$ , and  $A(p) = [1 + 2^{-p}\Gamma(0.5 - p)/\sqrt{\pi}] \approx 0.3222$ . The halo bias for the Sheth-Tormen mass function is given by

$$b_h(\nu) = 1 + \frac{a\nu^2 - 1}{\delta_c} + \frac{2p/\delta_c}{1 + (a\nu^2)^p}. \quad (3.21)$$

To make further progress we need to make some assumption about  $\langle N_{\text{qso}} \rangle(M)$  and  $\langle N_{\text{CIV}} \rangle(M)$ . We are assuming  $\langle N \rangle(M)$  to be of some functional form.

### 3.3.3 Density profiles of Halos

There are many studies that have attempted to determine the density profile of dark matter halos (Hernquist 1990; Navarro et al. 1997; Moore et al. 1999). The NFW profile proposed by Navarro et al. (1997) is the most commonly used dark matter profile. We are going to assume the NFW profile for our studies which is given as

$$\lambda(r|M) = \frac{\rho_s}{\left(\frac{r}{r_s}\right) \left(1 + \frac{r}{r_s}\right)^2} \quad (3.22)$$

where  $\rho_s$  and  $r_s$  are model parameters. A more frequent parametrization is the concentration parameter which is defined as  $c \equiv r_{\text{vir}}/r_s$ . Dark matter simulations, show that for halos of the same mass, the distribution of the concentration parameter is given by a log-normal distribution (Jing 2000; Bullock et al. 2001b).

$$p(c|M, z) \, \text{d}c = \frac{\text{d} \ln c}{\sqrt{2\pi\sigma_{\ln c}^2}} \exp\left(-\frac{\ln^2 c/\bar{c}(M, z)}{2\sigma_{\ln c}^2}\right) \quad (3.23)$$

where  $\sigma_{\ln c} \approx 0.25$  and  $\bar{c}(M, z)$  is given by

$$\bar{c}(M, z) = \frac{9}{1+z} \left( \frac{M}{M_\star(z)} \right)^{-0.13}, \quad (3.24)$$

where  $M_\star(z)$  is the characteristic mass at which  $\nu(M, z) = 1$ . The mass of the halo can be written as

$$M = \int_0^{r_{\text{vir}}} dr \, 4\pi r^2 \lambda(r|M) = 4\pi \rho_s r_s^3 \left( \ln(1+c) - \frac{c}{1+c} \right). \quad (3.25)$$

Hence mass  $M$  and concentration parameter  $c$  completely specify the density of dark matter halos. Since we have written our equation in Fourier space, the density profile can be written in Fourier space as

$$\lambda(k|M) = \frac{4\pi \rho_s r_s^3}{M} \times \left\{ \sin(kr_s) [\text{Si}((1+c)kr_s) - \text{Si}(kr_s)] - \frac{\sin(ckr_s)}{(1+c)kr_s} + \cos(kr_s) [\text{Ci}((1+c)kr_s) - \text{Ci}(kr_s)] \right\}, \quad (3.26)$$

where  $\text{Si}(x)$  and  $\text{Ci}(x)$  are given by equations

$$\text{Si}(x) = - \int_x^\infty dt \frac{\cos t}{t} \quad \text{and} \quad \text{Ci}(x) = \int_0^x dt \frac{\sin(t)}{t}. \quad (3.27)$$

### 3.4 DATA

In this study I am using data from the SDSS-III BOSS ([Eisenstein et al. 2011b](#)), described in § 2.4.1. For this study I am using the quasars identified by the survey and are part of Data Release 9 (DR9). The quasar selection process and properties are described in more detail in § 2.4.2.

Broad Absorption Lines (BALs) in quasar spectra are known to contaminate narrow absorption lines, so all spectra with C IV BALs, or Damped Lyman- $\alpha$  systems (DLAs), are removed from our analysis. The BOSS QSO catalog relies on visual examination to determine if an object is a QSO or not. All identified BAL systems are visually confirmed in all cases ([Pâris 2012](#), submitted). This process leads to a first-cut catalog of 35,367 C IV absorption systems.

Catalog absorbers with rest-frame equivalent widths,  $W_r$ , above  $3\text{\AA}$  can arise as artifacts of the pipeline (as, for example, to poorly subtracted night sky lines) or from complicated blends of multiple doublets. All systems with such strong  $W_r > 3\text{\AA}$  features are removed from the sample. This limit removes only 226 systems from our sample, leaving 35,141 absorbers.

For this study we need to ensure that our sample is close to complete. Low equivalent-width systems can only be observed in high signal-to-noise spectra. Figure 3.2 shows the signal-to-noise of the  $r$ -band SDSS photometry vs equivalent width. The solid black and dashed red lines are the median and mean respectively, in equivalent width bins of  $0.1\text{\AA}$ , for the absorbers above the horizontal line. The lines turn up toward higher  $\text{SN}_r$  to detect equivalent widths less the  $0.5\text{\AA}$  (vertical line). The lines are nearly constant towards the right of  $0.5\text{\AA}$ . The horizontal and vertical lines are the cuts  $\text{SN}_r > 6$  and  $W_r > 0.5\text{\AA}$ . After these cuts we are left with 9,276 absorption systems.

To demonstrate the completeness of the sample, I made a sample of weakest absorbers by selecting absorbers with a signal-to-noise in the  $r$ -band between 6.0 and 6.15, and rest equivalent-width between 0.50 and 0.55. There are total 34 systems satisfying the above criteria out of which I selected 6 systems randomly to show the significance of the absorber systems visually. Fig 3.3 shows the relevant part of the spectra which shows the C IV absorption system along with their equivalent width and signal-to-noise in  $r$ -band.

We choose C IV absorbers in the quasar spectrum in the observed wavelength range of  $3800\text{--}7500\text{\AA}$ . This range is chosen to avoid the noisy region of the spectra due to spectral contamination from sky lines on the spectra and our limited ability to correct for them. We also avoid any features in the region shortwards of  $1260\text{\AA}$  in the quasar rest-frame, as this region is contaminated by the N V line and the Lyman- $\alpha$  forest. Hence, our cut avoids many potential false detections at the expense of missing some real systems. This approach leads to a redshift range for detectable C IV systems of  $1.453 < z < 3.841$ . The redshift cut corresponding to this wavelength restriction is shown in Eq. 2.9 using  $\beta_{\text{min}} = -0.01$ . These cuts reduce the sample size to 7,753.

There are some skylines which can lead to false identifications of C IV lines. The oxygen line at  $5577\text{\AA}$ , and the sodium doublet at  $5890\text{\AA}$  are the two prominent ones. To remove

Table 3.1 Table of  $N_{\text{CIV}}$  for different selection cuts

Description	$N_{\text{CIV}}$
No cut	35,367
$W_r < 3 \text{ \AA}$	35,141
$W_r > 0.5 \text{ \AA}$	25,311
$\text{SN}_r > 6$	9,276
$\text{FWHM} < 600 \text{ km s}^{-1}$	9,276
$3800\text{\AA} \leq \lambda_r < 7500\text{\AA}$	7,753
$\lambda_o < 5550 \text{ \AA}, \lambda_o > 5620 \text{ \AA}$	7,638
$\lambda_o < 5850 \text{ \AA}, \lambda_o > 5950 \text{ \AA}$	7,507

any possible problem due to these lines we apply cuts removing any absorption systems in the observer-frame wavelength of  $5550 \text{ \AA} < \lambda_o < 5620 \text{ \AA}$  and  $5850 \text{ \AA} < \lambda_o < 5950 \text{ \AA}$ . These cuts further reduce the sample size to 7,507 systems.

These cuts and their corresponding number of absorbers are tabulated in the Table 3.1.

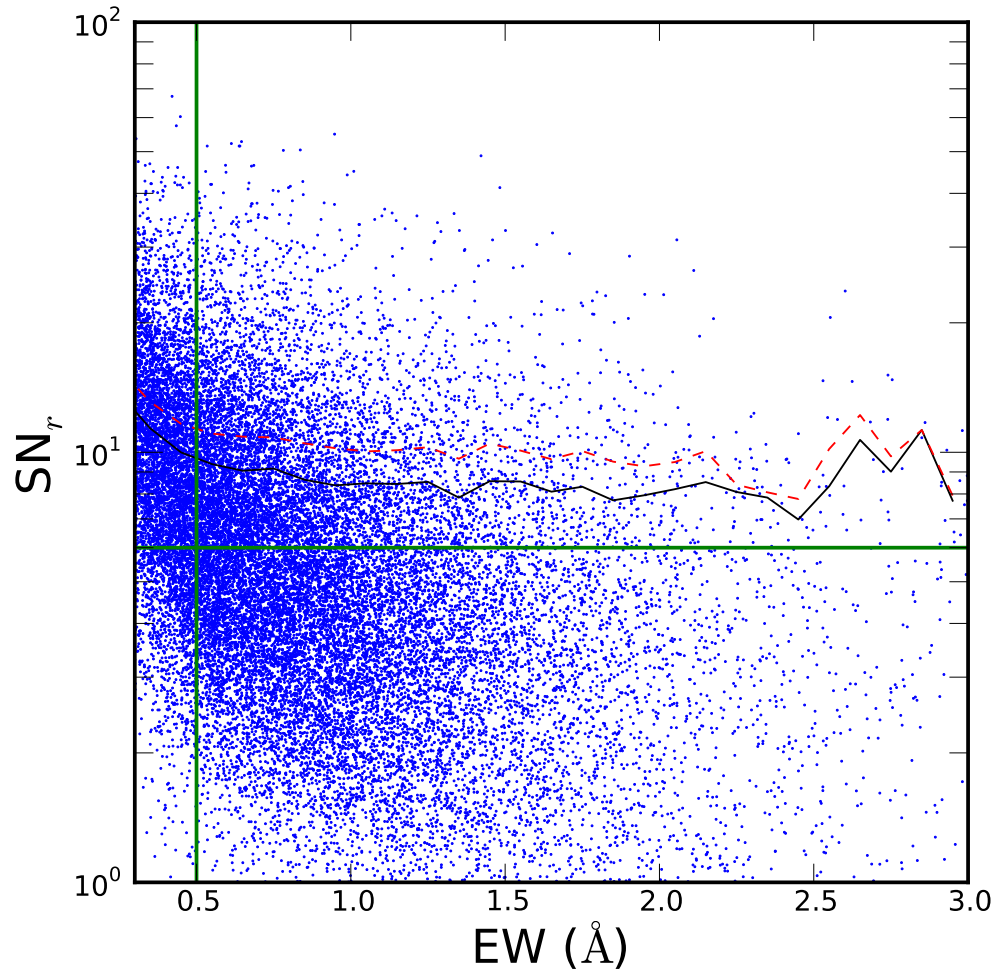


Figure 3.2  $r$ -band signal-to-noise of the back-light quasars vs EW of detected CIV. The green lines are the sample cut ( $W_r > 0.5 \text{\AA}$ ,  $SN_r > 6$ ). The red dashed and black solid lines are the mean and median of  $SN_r$  in  $W_r$  bins of  $0.1 \text{\AA}$  for the absorbers above the horizontal line.

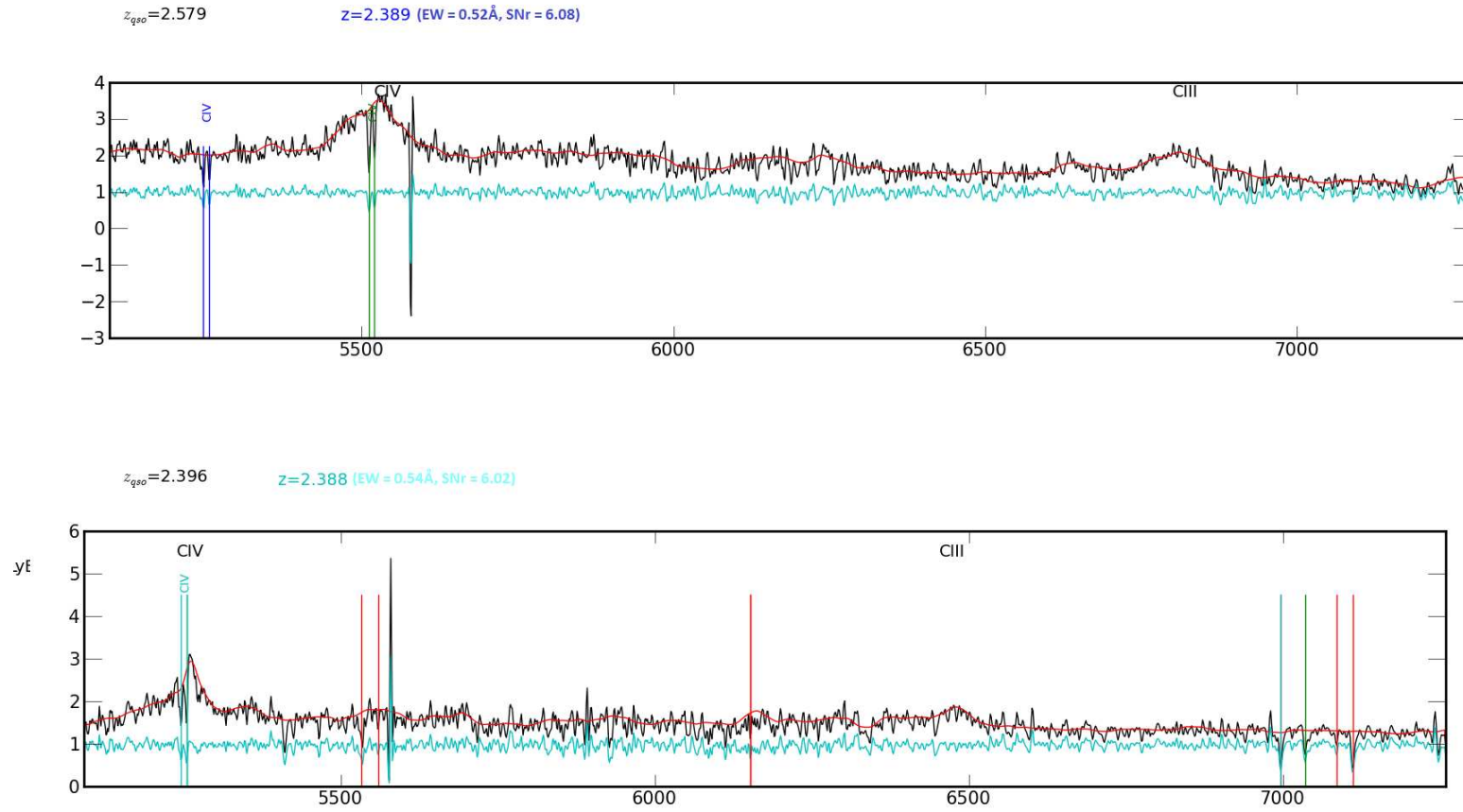


Figure 3.3 First and second of six example spectra.

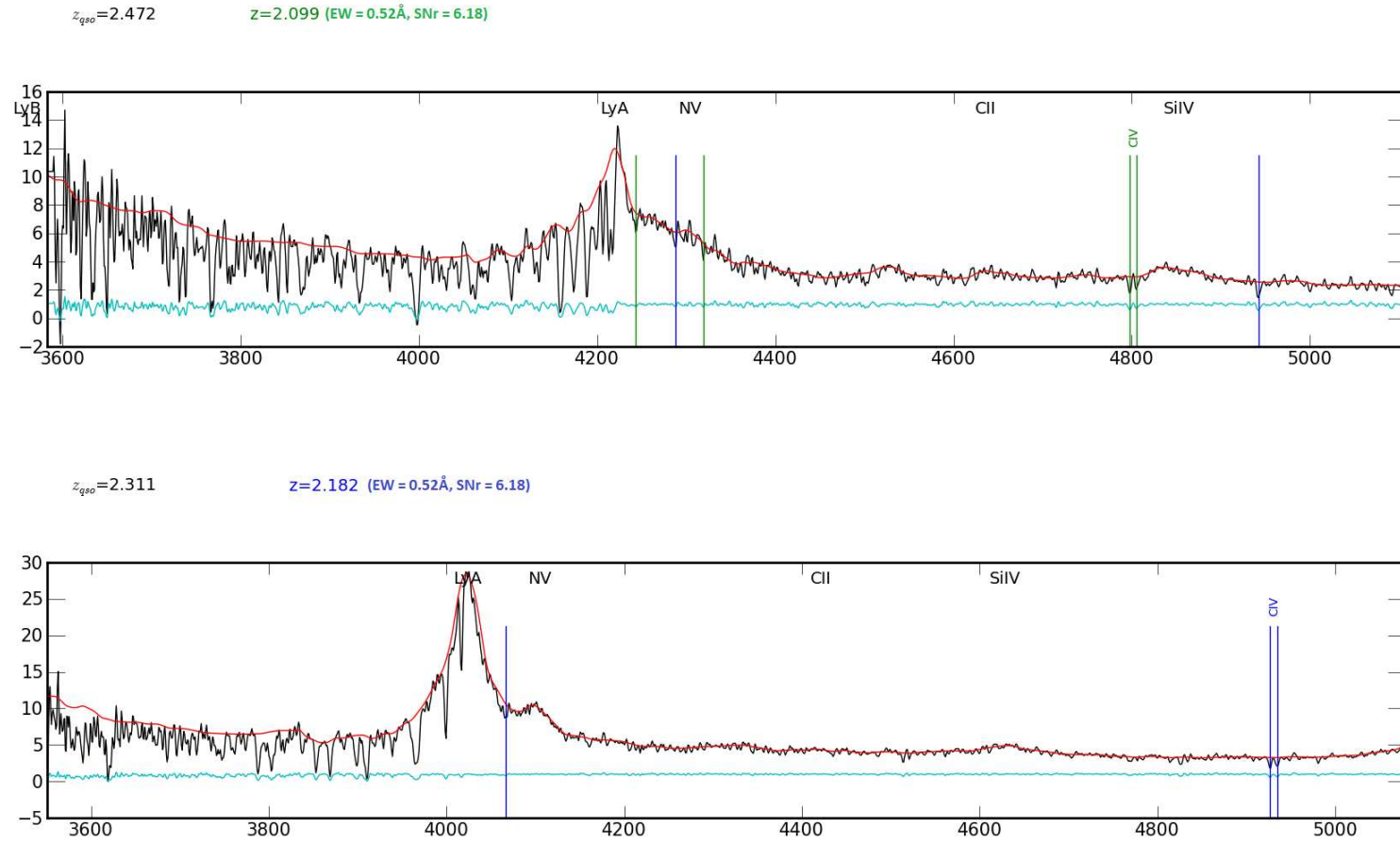


Figure 3.3 Third and fourth of six example spectra.



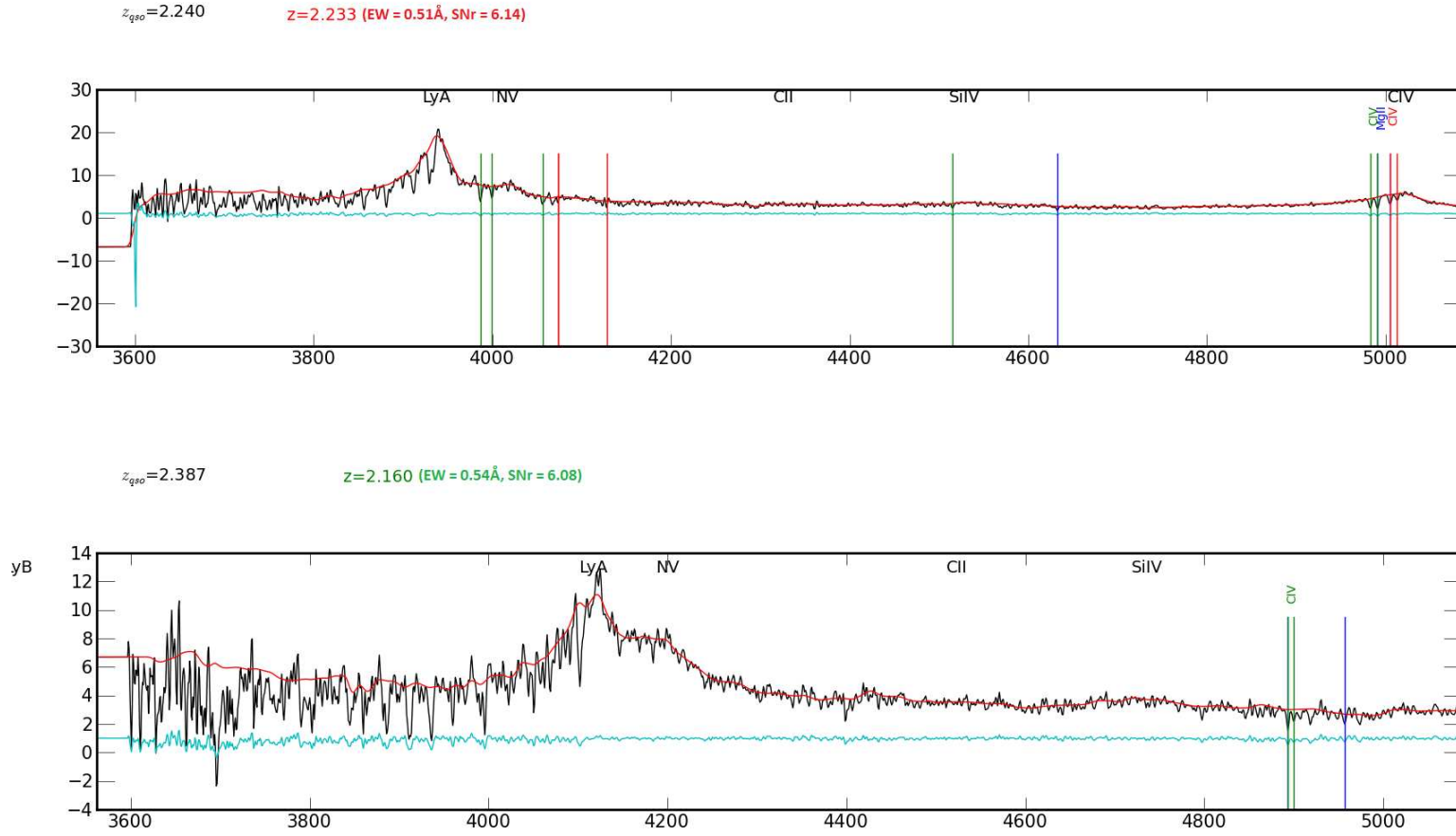


Figure 3.3 Example of six spectra out of thirty four weakest defined by signal-to-noise  $r$ -band between 6.0 and 6.15, and equivalent-width are between 0.50 and 0.55. The C IV are evident in these spectra and suggest the sample to be complete. The equivalent-width and signal-to-noise of  $r$ -band are also mentioned in the spectrum.

This analysis is done in the quasar rest frame. Because quasars at different redshift contributed to different range of observable velocity space, I calculate the number of quasars that contribute to any particular velocity range. Fig. 3.4 shows the number of quasars contributing as a function of velocity from the quasar rest-frame. As can be seen from this plot there are typically  $\sim 12,300$  quasars that contribute to the velocity range of interest.

### 3.5 ESTIMATION OF THE CROSS-CORRELATION FUNCTION

Using the halo model formalism described in section 3.3 we estimate the cross-correlation function of quasars and C IV absorbers. Using the estimation given in Eq. 3.8. I used the result from (Vikas et al. 2012, submitted to ApJ) of a large scale bias for quasars of  $b_{\text{qso}} = 3.71$  and for C IV absorbers  $b_{\text{CIV}} = 2.38 \pm 0.62$  at redshift  $\langle z \rangle = 2.3$ . I use the large scale bias estimation to determine the small scale bias. For this I have to assume,  $\langle N \rangle(M)$ , the functional form of average number of quasars and C IV absorbers in a halo of mass  $M$ . For quasars I assume  $\langle N \rangle(M)$  to be of the form

$$\langle N \rangle(M) = \begin{cases} 0 & \text{for } M < M_{\min} \\ 1 & \text{Otherwise} \end{cases} \quad (3.28)$$

The form of the above equation is motivated by the fact that the quasars are highly clustered objects and hence are expected to live in large DM halos (Ross et al. 2009; White et al. 2012). The time scale for SMBH merger is short ( $\sim 10^5$  years) hence we do not expect more than one quasar in a DM halo (Armitage and Natarajan 2002).

Now, using Eq. 3.19 I estimate  $M_{\min}$  such that at very small  $k$  (large scale) the bias matches the scale independent bias. I perform a similar calculation for C IV absorbers with a slightly different  $\langle N \rangle(M)$  functional form. For C IV absorbers I assume

$$\langle N \rangle(M) = \begin{cases} 0 & \text{for } M < M_{\min} \\ \frac{M}{M_{\min}} & \text{Otherwise} \end{cases} \quad (3.29)$$

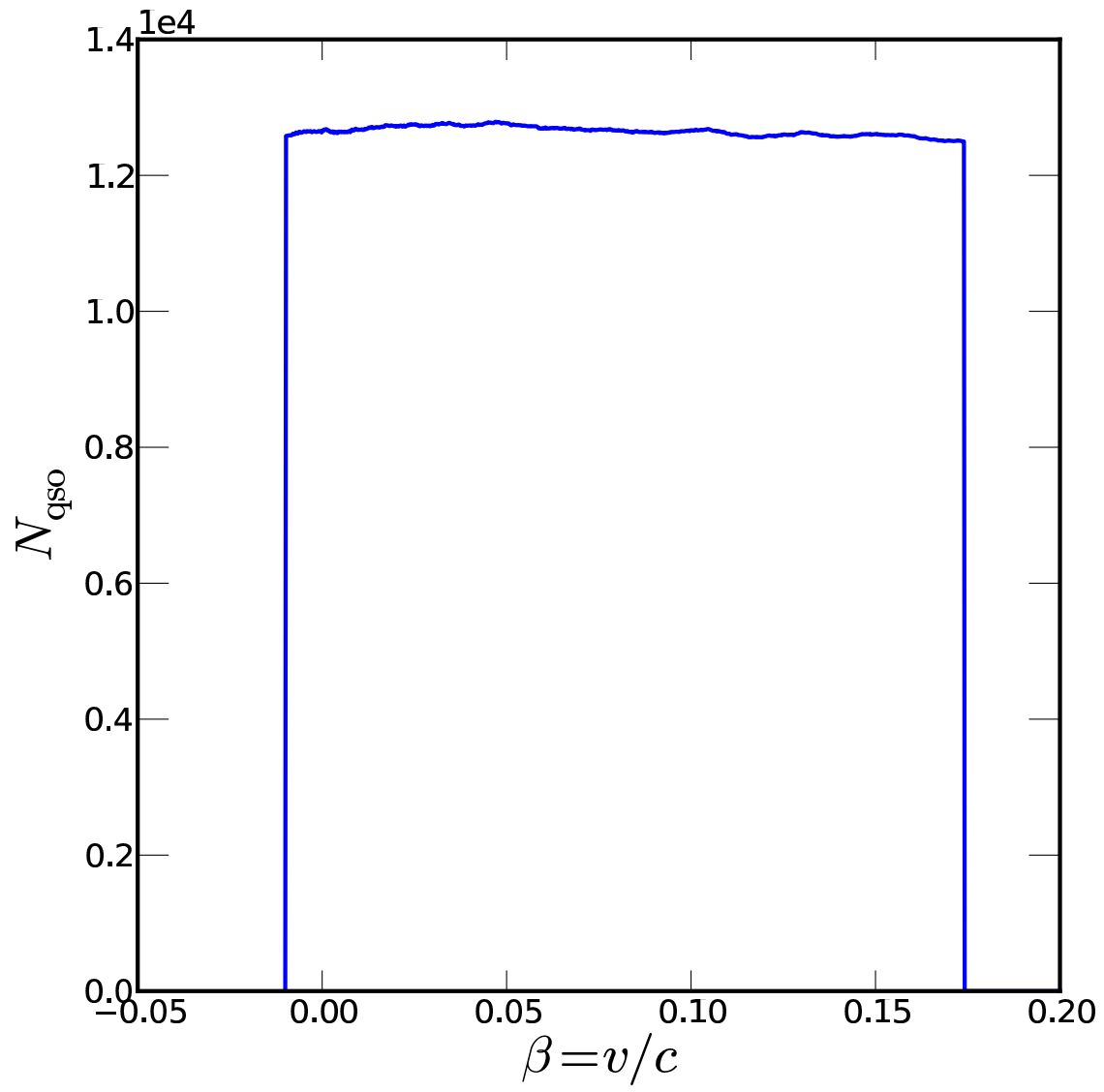


Figure 3.4 Number of quasars contributing at any given velocity in the rest-frame of quasar.

Table 3.2 Estimated parameters, using HOD formalism, for the Quasars and C IV absorbers so that the linear bias is correct.

	Quasars	C IV absorbers
$b$	3.71	2.37
$M_{\min}$	$2.61 \times 10^{12}$	$7.66 \times 10^{10}$

The clustering of C IV absorbers is similar to galaxies (Vikas et al. 2012). Hence we may expect many C IV absorbers to occupy a single DM halo. Hence the form of the above equation does not limit the number of absorption systems in a halo.

We estimate the  $M_{\min}$  which matches the scale-independent bias for C IV absorbers. Table 3.2 lists the estimated  $M_{\min}$  for both C IV absorbers and quasars. Fig. 3.5 shows the bias as a function of minimum mass for both functional forms. We denote the minimum mass and bias for C IV and quasars in the plot.

The power spectrum of the cross-correlation function from the two-halo term can be written using Eq. 3.18. I get the cross-correlation function from the power spectrum using an inverse Fourier transform.

$$\xi_{\text{qso,CIV}}^{2h}(r) = \frac{1}{2\pi^2} \int k^3 b_{\text{qso}}(k) b_{\text{CIV}}(k) P^{\text{lin}}(k) \frac{\sin(kr)}{kr} d \ln k \quad (3.30)$$

The measurements of large-scale bias for quasars and C IV absorbers are estimated at redshift  $z \sim 2.3$ . Hence the cross-correlation function we estimated is only valid at about the same redshift. Since our quasar sample for this study has a larger redshift range ( $1.5 < z < 3.8$ ) we need to estimate the cross-correlation function at various redshifts. In the absence of any knowledge of the rate of change of the large-scale bias with respect to redshift I assume that the large-scale bias for quasars remains the same in our redshift range of interest. Thus any change in the cross-correlation is governed by the change in the linear power spectrum due to redshift.

Figure 3.6 shows the cross-correlation function of the two-halo term at redshifts  $z = 2.0$  and 2.4. The cross-correlation function for  $z = 2.3$  is calculated using the halo occupation model formalism and that for at  $z = 2.0$  is calculated from the values at  $z = 2.3$  using the redshift evolution of the linear power spectrum of dark matter.

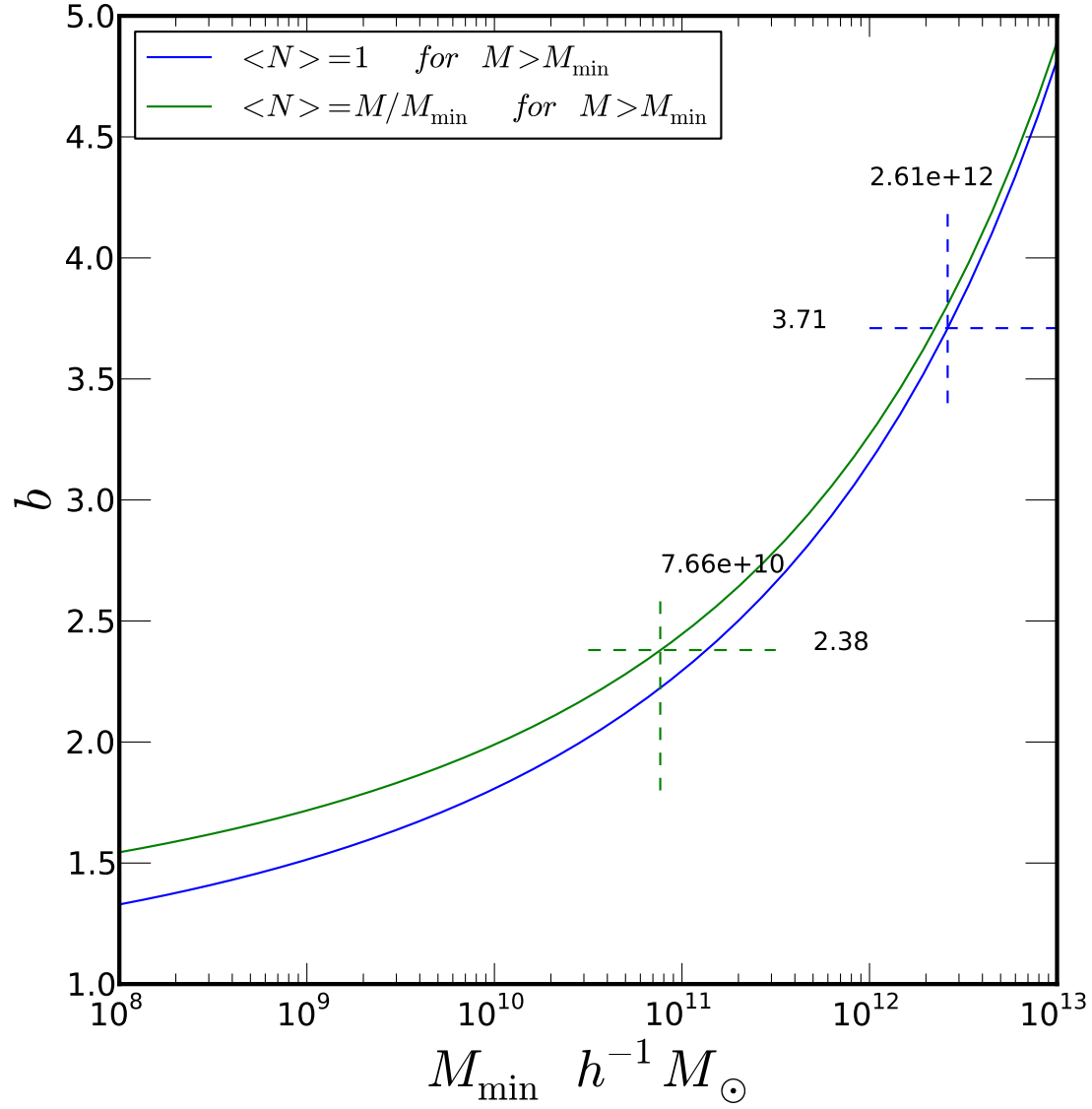


Figure 3.5 Plot of bias vs minimum mass. The two curves correspond to different functional forms for the average number of objects in a halo of given mass. The scale-independent bias and minimum halo mass corresponding to them is marked.

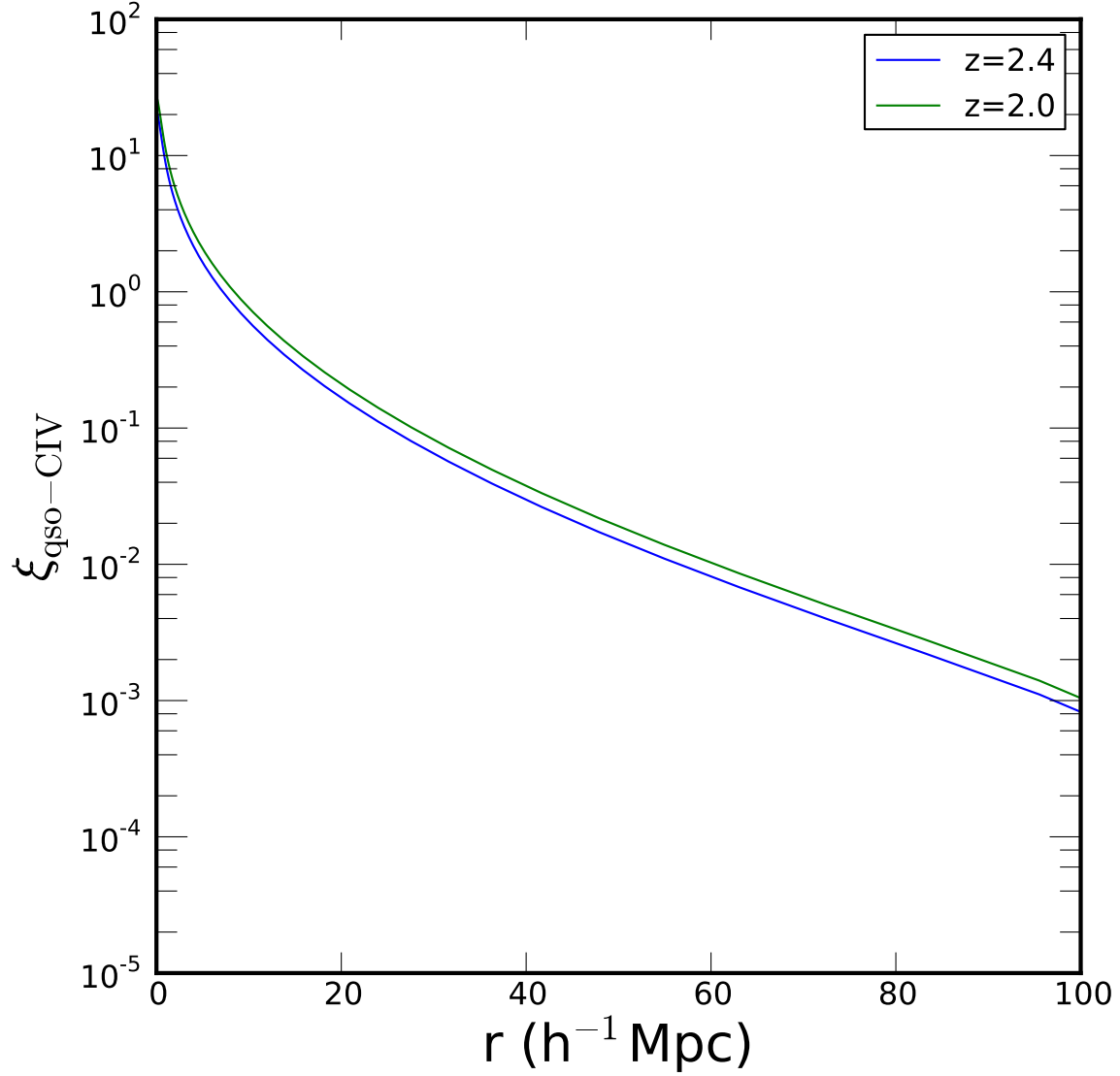


Figure 3.6 Plot of the quasar CIV absorber cross-correlation function for redshift 2.0 and 2.4 . The  $z = 2.3$  line is calculated using the halo occupation formalism and  $z = 2.0$  is calculated using the estimate of  $z = 2.4$  and the growth function of the linear power spectrum.

### 3.6 RESULTS

In this section I present the results of the different analysis and the inference that can be drawn from them.

### 3.6.1 Estimation of parameters for the full dataset

I fit the model described by Eq. 3.10 to the observed BOSS data. I assume the redshift error of BOSS quasars to be  $\Delta z_{\text{qso}} = 0.003(1 + z_{\text{qso}})$  (White et al. 2012). Figure 3.7 shows the number density per unit velocity of the C IV absorbers as the blue circles. The error-bar on the data is the Poisson error on the bin. The solid black line is the best fit model to the data. The green region around the model line is the  $1-\sigma$  error region of the model. The error region is estimated by making 1000 realizations of the best fit covariance matrix and calculating the  $1-\sigma$  spread around every point. The best-fit parameters and their associated errors are listed in Table 3.3.

Figure 3.8 shows the different components of the best-fit model. The solid line is the one-halo component of the number density, Eq. 3.8, and the red region around the line is the  $1-\sigma$  error region. The dashed line is the two halo component of the number density, Eq. 3.6 and the green region is the  $1-\sigma$  error. The dotted line is the outflow component of the number density, Eq. 3.9, and the blue region is  $1-\sigma$  error region.

Figure 3.9 shows the correlation matrix at the best-fit value in parameter space. The plot shows that there are some significant correlations between parameters of each models. However, the lack of correlation between the outflow parameters ( $n_{2k}$ ,  $n_{4k}$ ,  $n_{6k}$ ) and non-outflow parameters ( $n_0\sigma_0$ ,  $\epsilon$ ,  $\sigma_\beta$ ,  $f$ ) is evident. This suggest that our estimation of the existence and overall strength of the outflow component is quite robust. There is also a lack of correlation between the one-halo parameters ( $f$ ,  $\sigma_\beta$ ) and two-halo parameters ( $n_0\sigma_0$ ,  $\epsilon$ ) implying that our models are each independently constrained by the data.

### 3.6.2 Luminosity Dependence for Outflow

In this section I explore the dependence of the outflow on the luminosity of the quasars. To explore this, I calculated the absolute magnitude of the backlighting quasars. I divide the C IV absorbers into three bins ( $\approx 2500$  absorbers each) according to tritiles of absolute magnitude. Figure 3.10 shows the distribution of the absolute magnitude of the back-lighting quasars of absorbers. The red-dashed lines show the tritiles of absolute magnitude of the sample. For sub-samples I fit the model again fixing the non-outflow parameters ( $n_0\sigma_0$ ,  $\epsilon$ ,

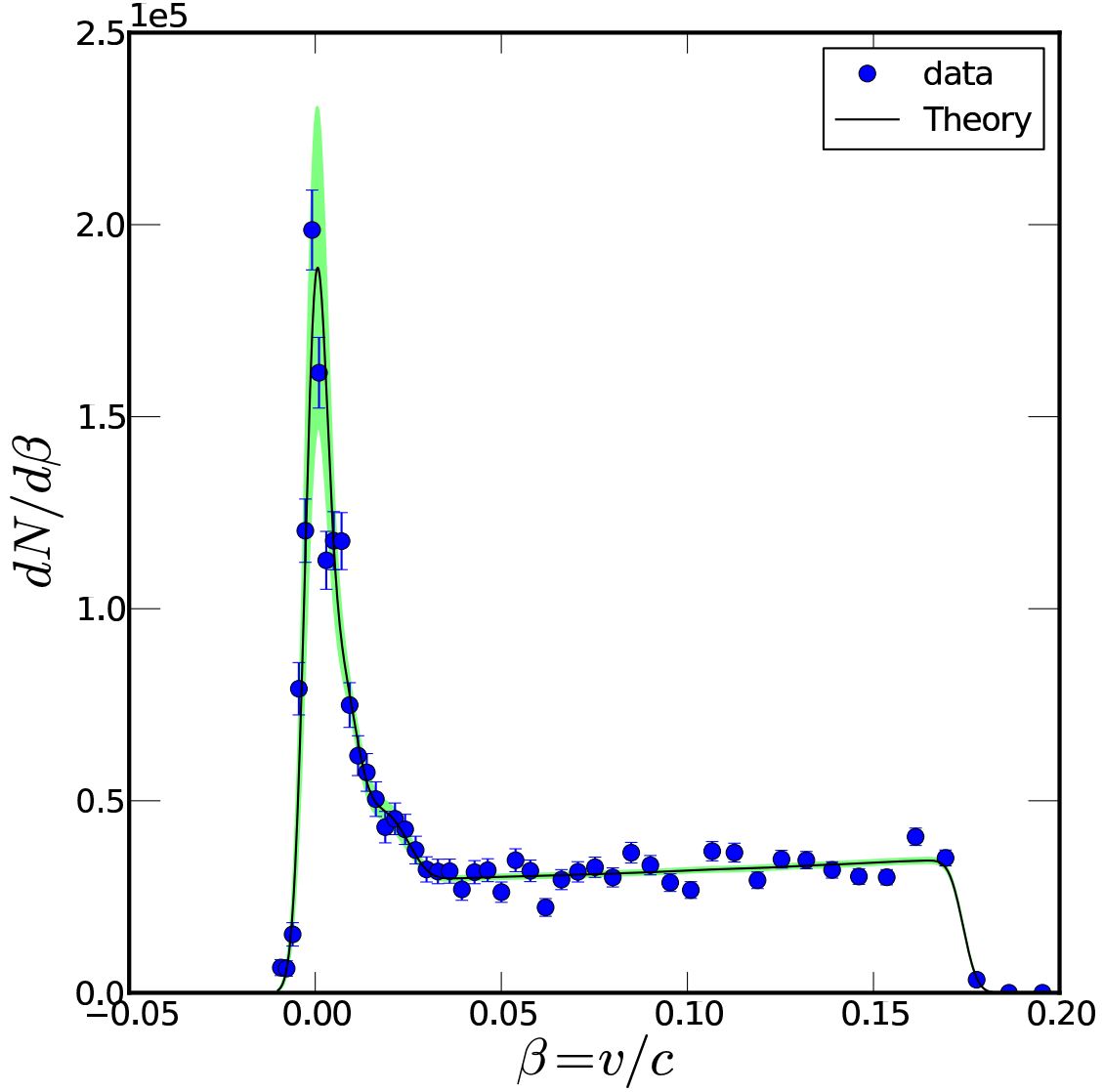


Figure 3.7 The model number density (solid line) and the observed number density (blue circles) of the C IV absorbers as a function of velocity in the rest frame of the quasar. The error-bar on the data is estimated assuming Poisson distribution in the bins. The error region for the model is derived by calculating the  $1-\sigma$  error at every velocity point in 1000 realizations of the best-fit covariance matrix.



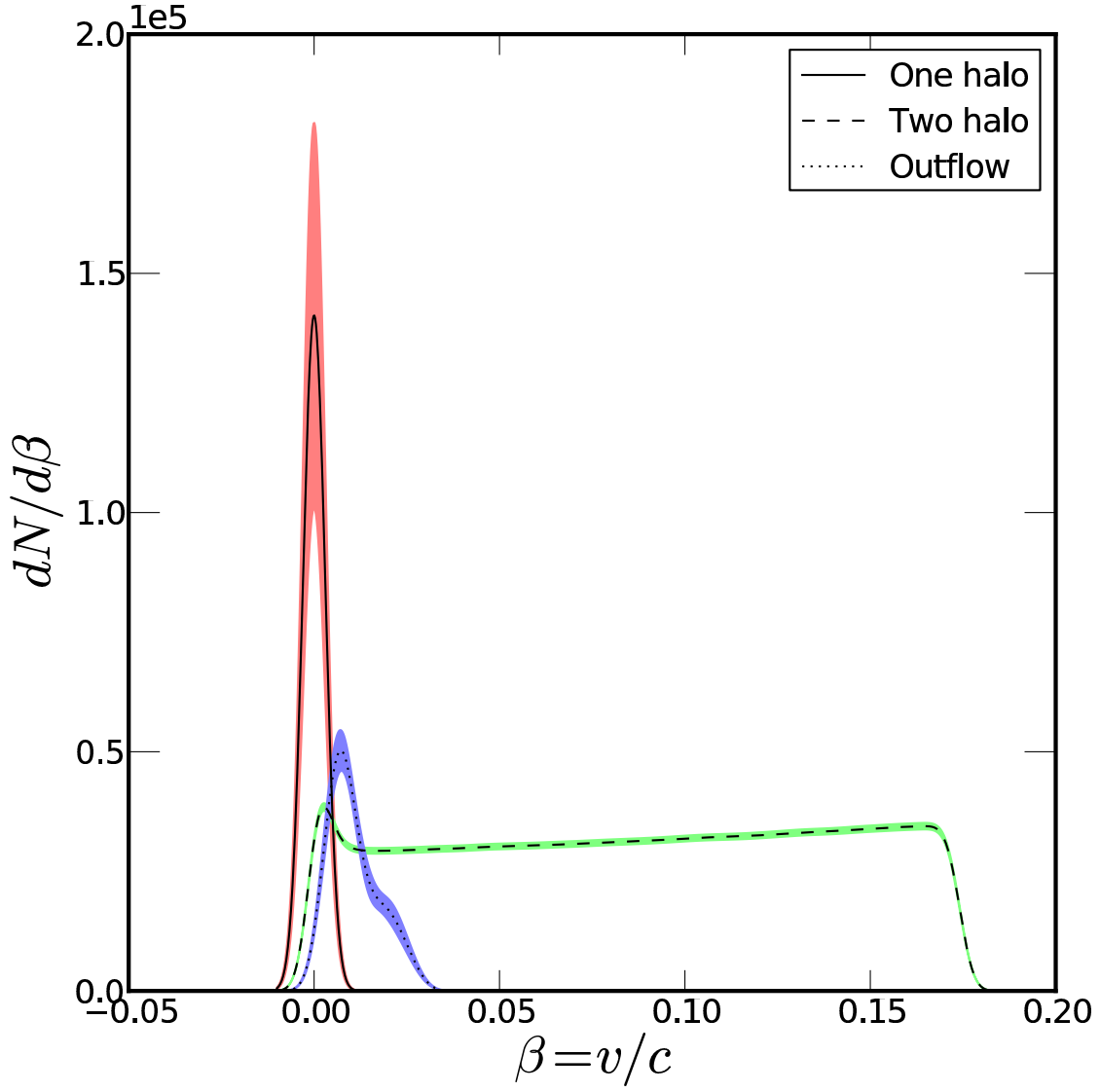


Figure 3.8 The individual components of the best-fit model. The one halo, two halo, and outflow components are denoted by solid line, dashed line, and dotted line respectively with red, green, and blue region as their  $1\text{-}\sigma$  error region.

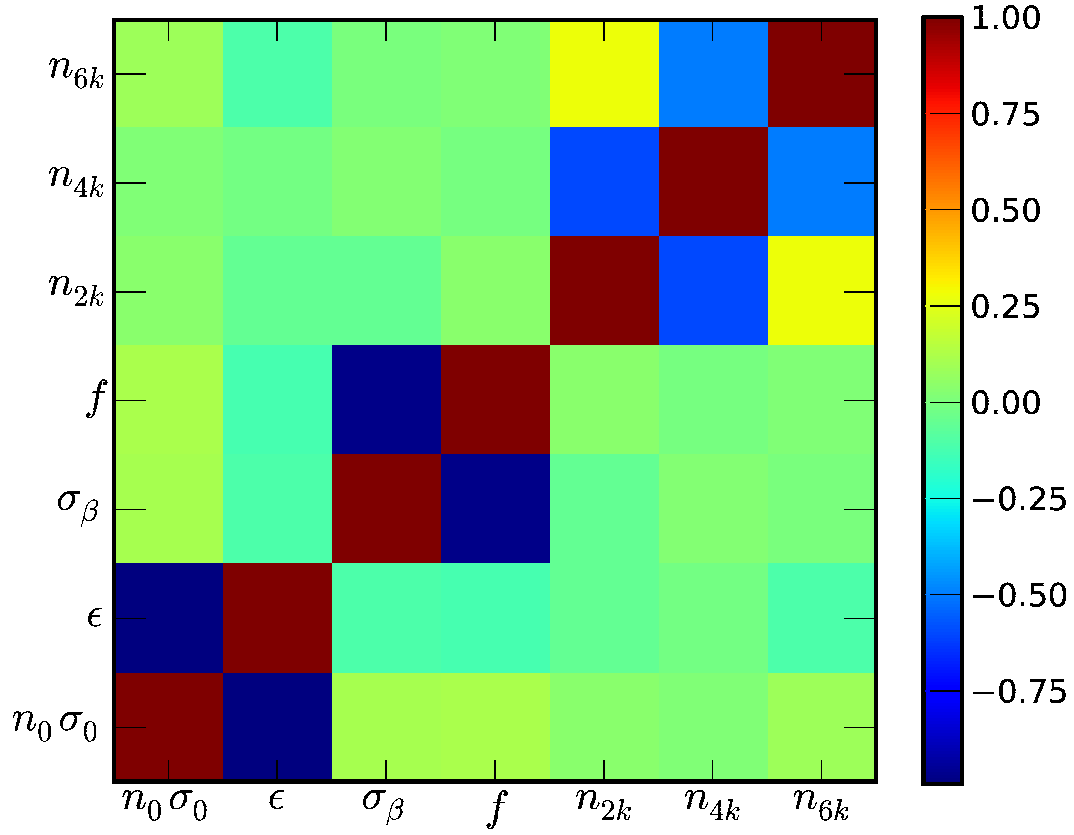


Figure 3.9 Correlation matrix of the best-fit model. The existence of many significant correlations between parameters is evident. However, the lack of correlation between outflow parameters ( $n_{2k}$ ,  $n_{4k}$ ,  $n_{6k}$ ) and non-outflow parameters ( $n_0\sigma_0$ ,  $\epsilon$ ,  $\sigma_\beta$ ,  $f$ ) is also clear, which suggests the robustness of the outflow detection.

Table 3.3 The best-fit parameters of the model for all absorber data.

Parameter	Best Fit
$n_0\sigma_0$	$1.558 \pm 0.188 \times 10^{-3} \text{ Mpc}^{-1}$
$\epsilon$	$-2.884 \pm 0.107$
$\sigma_\beta$	$3.451 \pm 1.925 \times 10^{-4} \text{ km s}^{-1}$
$f$	$8.091 \pm 4.519 \times 10^3$
$n_{2k}$	$5.736 \pm 0.613$
$n_{4k}$	$1.373 \pm 0.485$
$n_{6k}$	$1.540 \pm 0.304$

$\sigma_\beta$ ,  $f$ ) to be same as the best-fit of the entire sample (shown in Table 3.3). I allowed the outflow parameters ( $n_{2k}$ ,  $n_{4k}$ ,  $n_{6k}$ ) to vary and get the best-fit outflow parameters for each sub-sample. Table 3.4 shows the best-fit outflow parameters for the high (low), medium (medium), and low (high) absolute magnitude (luminosity) sample. Figure 3.11 shows the best-fit outflow components for the low, medium and high absolute magnitude samples. The red, green and blue line shows the outflow component for low, medium, and high luminosity samples respectively. This plot gives strong evidence of the outflow being at higher velocity for the brighter quasars compared to lower brightness one.

I also try to estimate if there is any dependence of the number of outflow systems on the quasar luminosity. Table 3.5 lists the expected number of CIV systems for each component as a percentage of the expected total. I calculate the expected number for each given component by integrating the component for the whole range of  $\beta$ . It is evident that the abundance of the outflow component for low, medium and high luminosity are consistently decreasing with increasing luminosity. An inference can be drawn from these observations that the luminosity tends to push absorption systems to higher velocity, while destroying a fraction of absorbtion systems. Table 3.6 shows the number-density-weighted mean velocity of the outflows for the three different samples and for all absorbers.

Table 3.4 The best-fit parameters of the model for all absorber data.

Parameter	$M_r < -27.09$	$-27.09 < M_r < -26.45$	$M_r > -26.45$
$n_{2k}$	$3.188 \pm 0.826$	$5.774 \pm 0.978$	$7.459 \pm 1.102$
$n_{4k}$	$1.122 \pm 0.712$	$0.651 \pm 0.813$	$2.905 \pm 0.948$
$n_{6k}$	$1.693 \pm 0.482$	$1.588 \pm 0.520$	$0.840 \pm 0.529$

Table 3.5 Individual component as a percent of the total sample.

Sample	One Halo	Two Halo	Outflow
$M_r < -27.09$	$13.46 \pm 0.50\%$	$78.57 \pm 0.05\%$	$7.97 \pm 0.15\%$
$-27.09 < M_r < -26.45$	$13.20 \pm 0.52\%$	$77.47 \pm 0.05\%$	$9.33 \pm 0.15\%$
$M_r > -26.45$	$16.52 \pm 0.64\%$	$71.34 \pm 0.05\%$	$12.13 \pm 0.16\%$
All	$14.32 \pm 0.57\%$	$75.46 \pm 0.05\%$	$10.23 \pm 0.09\%$

Table 3.6 The weighted mean velocity of the outflow.

Sample	Velocity $\text{km s}^{-1}$
$M_r < -27.09$	$3786 \pm 77$
$-27.09 < M_r < -26.45$	$3191 \pm 63$
$M_r > -26.45$	$2902 \pm 49$
All	$3232 \pm 34$

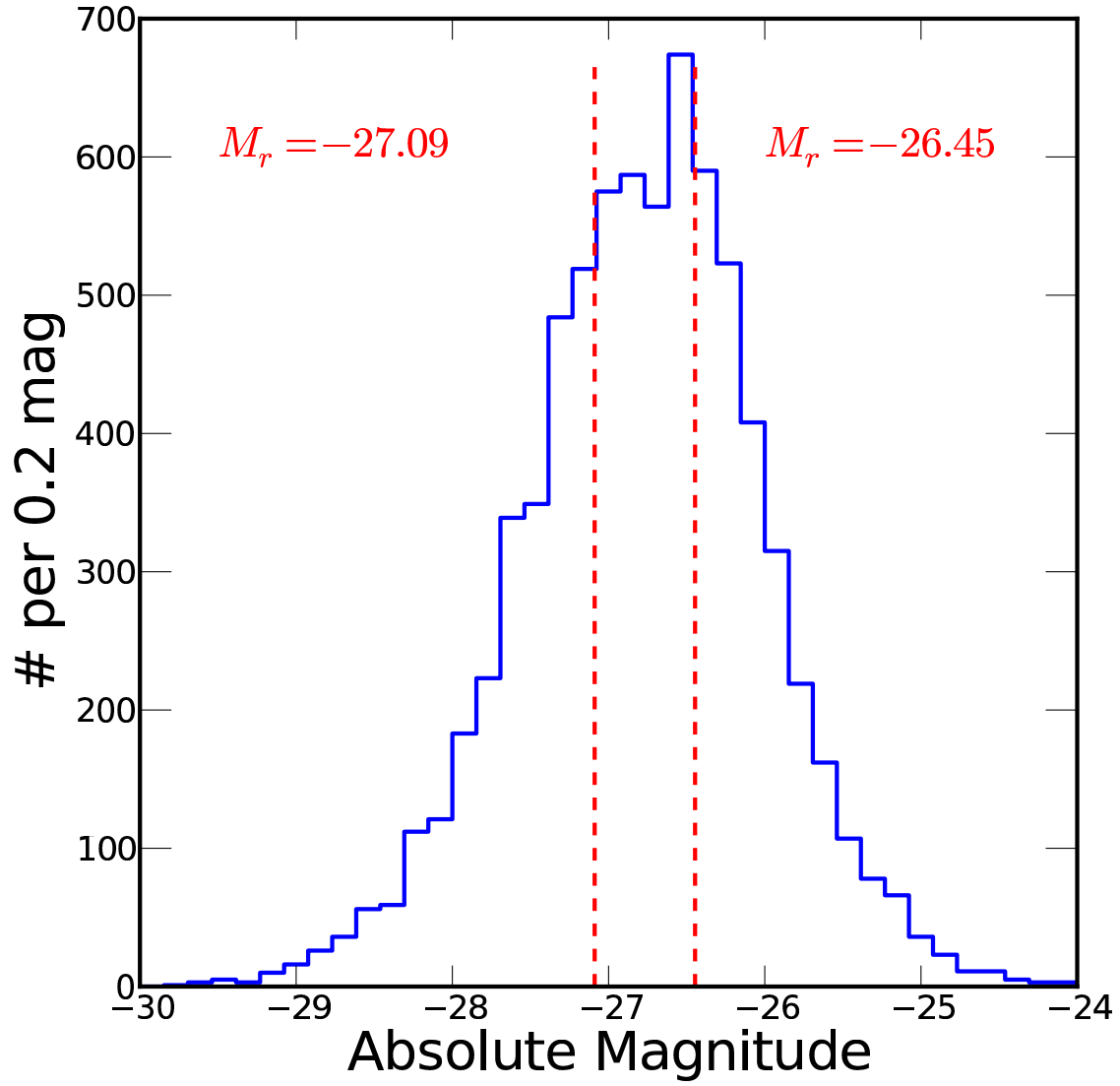


Figure 3.10 Distribution of the absolute magnitude of the back-lighting quasars of absorbers. The red-dashed lines indicate the tritiles of the sample (-27.09,-26.45) mag.

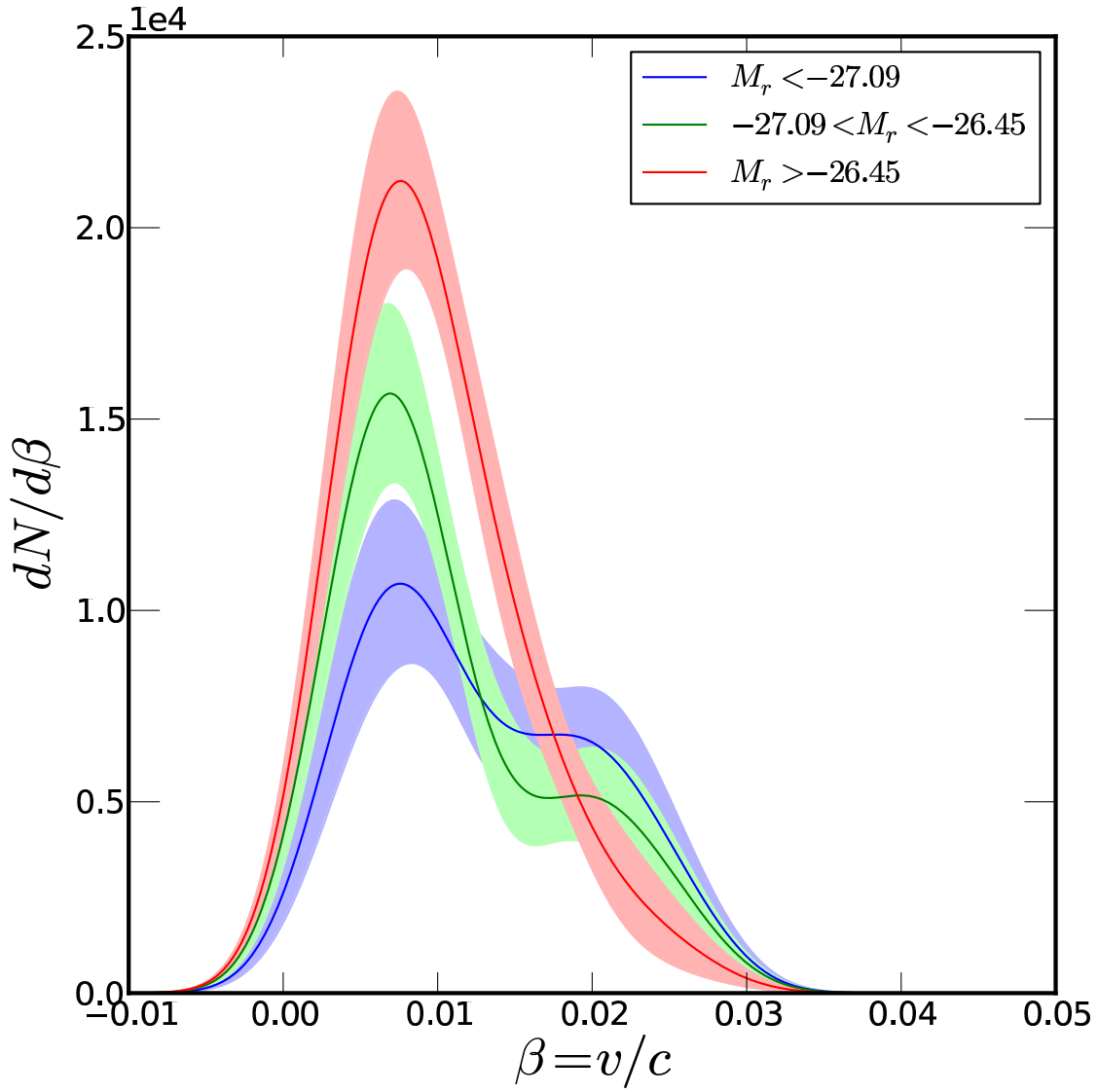


Figure 3.11 Outflow component of the low, medium and high luminosity samples. The red, green and blue lines are outflows from low, medium and higher luminosity sample and the red, green and blue regions around them are the  $1-\sigma$  errors of the outflows. The total number of systems is smaller (higher) for brighter (dimmer) quasars.

### 3.6.3 Outflowing absorber properties

In this section I explore the properties of the CIV absorption systems of different components. Since the spectra from the BOSS survey are of low resolution there are only a few properties that can be extracted from the absorption feature. The main properties are the equivalent width (EW) and the Full-Width-at-Half-Max (FWHM). The equivalent width is defined in §2.1 in detail. FWHM is defined as the width of the feature at the half of the “maximum” (deepest point for the absorption feature).

**3.6.3.1 FWHM of outflowing absorbers** At large velocities ( $> 15,000 \text{ km s}^{-1}$ ;  $\beta > 0.05$ ) in the quasar rest-frame the absorbers are largely found in the intervening material between the quasars and us. These absorbers are unlikely to be affected by quasar radiation and winds. The normalized distribution of FWHM for these absorbers in the two-halo component is shown as blue circles in Fig. 3.12. The error-bars are the Poisson errors. I now take the distribution of FWHM in the range of  $-0.01 < \beta < +0.04$  which has a significant contribution from both the one-halo and outflow components. I estimate the number of absorbers in this range from the two-halo component by integrating the two-halo component in the mentioned  $\beta$  range. Assuming that these two-halo absorbers have the same distribution of FWHM as calculated for ( $v > 15,000 \text{ km s}^{-1}$ ), I subtract that component and deduce the normalized distribution of FWHM for the one-halo and outflow components. This is shown as the green points in Fig. 3.12.

From the plot it is evident that there are significant differences in the distribution of FWHM between the components which could be affected by quasars and components which are not affected by quasars. I conclude that absorbers have systematically smaller FWHM due to either the affect of quasar radiation or outflow, or that quasar environments produce CIV absorbers of smaller FWHM.

I further analyze the data to see if there is any systematic difference in the distribution of FWHM for the one-halo and outflow components. To isolate their distribution I choose a range  $+0.01 < \beta < +0.04$  in which there is little contribution of the one-halo component which is mostly  $-0.01 < \beta < +0.01$ . Using the distribution of the two-halo component, shown

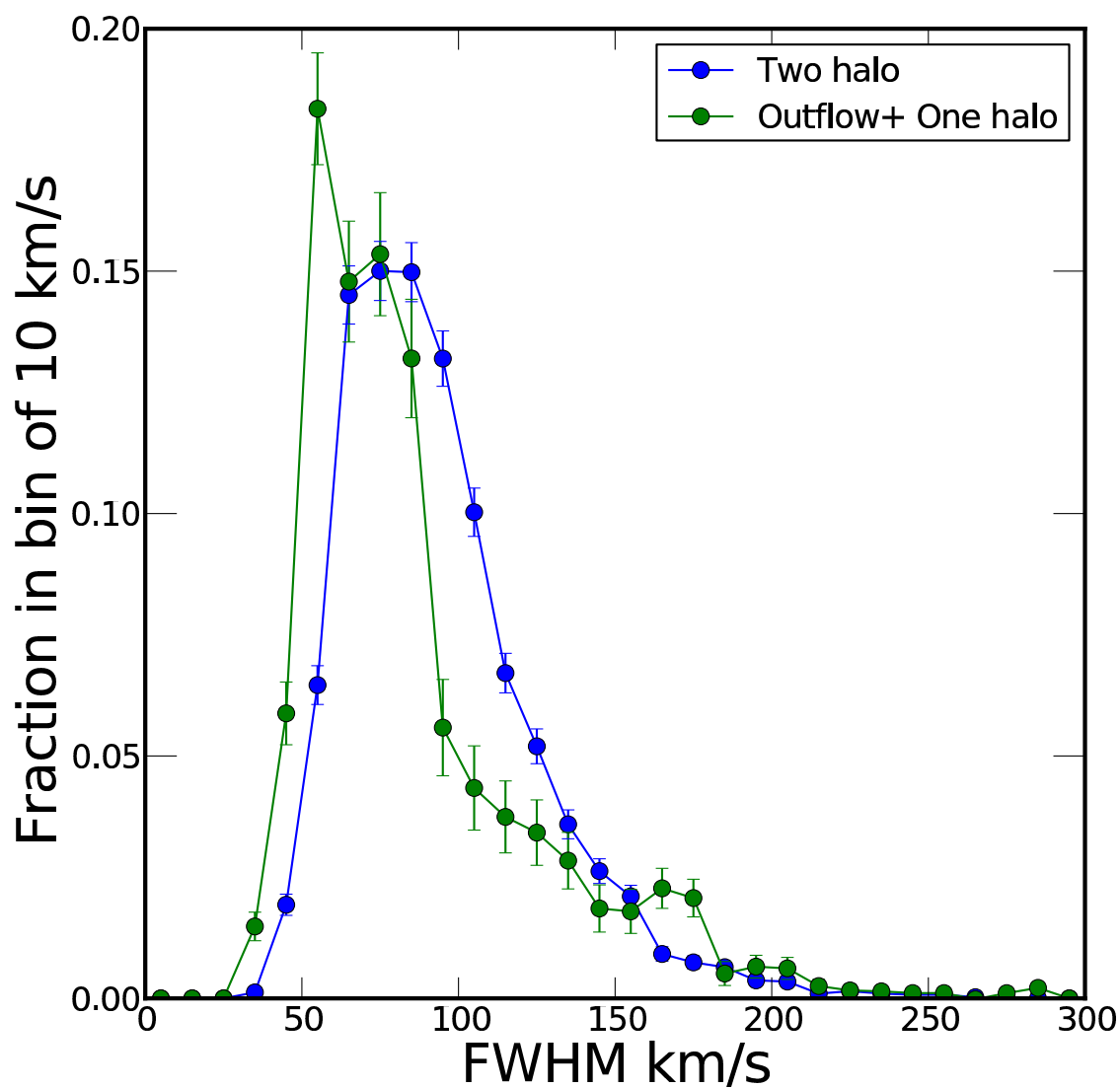


Figure 3.12 Normalized distribution of FWHM for the two-halo (blue) and one-halo plus outflow (green) C IV absorption systems. The two distributions are significantly different and suggest systematically smaller FWHM for the absorbers affected by quasars.



as the blue points in Fig. 3.13, I determine the normalized distribution for the outflow component which is shown as green points in the figure. For the range  $-0.01 < \beta < +0.01$  there is a significant contribution of the outflow as well as the two-halo terms. Assuming the distribution of the other components, I determine the normalized distribution of the one-halo component, which is shown as red points in the figure.

The FWHM distributions of outflow and one-halo absorbers in Figure 3.13 are quite noisy. It is difficult to quantify the difference between the one-halo and outflow distributions. However, the outflow component does show an excess at lower FWHM. It can be inferred that the outflow components have a systematically lower FWHM compared to both two-halo and one-halo components. The estimate of the outflow and one-halo distributions are very anti-correlated as they are isolated from the combined distribution. This anti-correlation makes the differences, appear up to two times larger than they actually are. I used a Kolmogorov–Smirnov (KS) test to test the significance of difference between the one-halo and outflow components. The null hypothesis is that the distribution of one-halo and outflow FWHMs are the same. I made 1000 realizations of the FWHM distribution by shuffling the FWHM of the absorbers in the range  $-0.01 < \beta < +0.04$ . For each realization I estimated the “ks-distance” between the one-halo and outflow distribution as the maximum difference between the cumulative distribution of the two samples. The distribution of the ks-distance is shown in Figure 3.14. The red dashed line shows the ks-distance of outflow and one-halo distribution from Figure 3.13. It is evident that the significance of the difference is high (p-value  $\sim 0.001$ ). The p-value value signifies the probability of getting the same result by chance. I conclude that the FWHM of the absorbers in outflow is different compare to the one in the host halo of the quasars.

**3.6.3.2 Equivalent width of outflowing absorbers** I follow a similar approach for estimating the distribution of equivalent width as I did for FWHM in §3.6.3.1. Figure 3.15 shows the normalized distribution of equivalent width for the two-halo component in blue points and the one-halo plus outflow in green. The two-halo component is derived from the absorbers with velocity ( $> 15,000 \text{ km s}^{-1}$ ). The one-halo plus outflow component is derived from  $-0.01 < \beta < +0.04$ , subtracting the two-halo component. It is evident from the

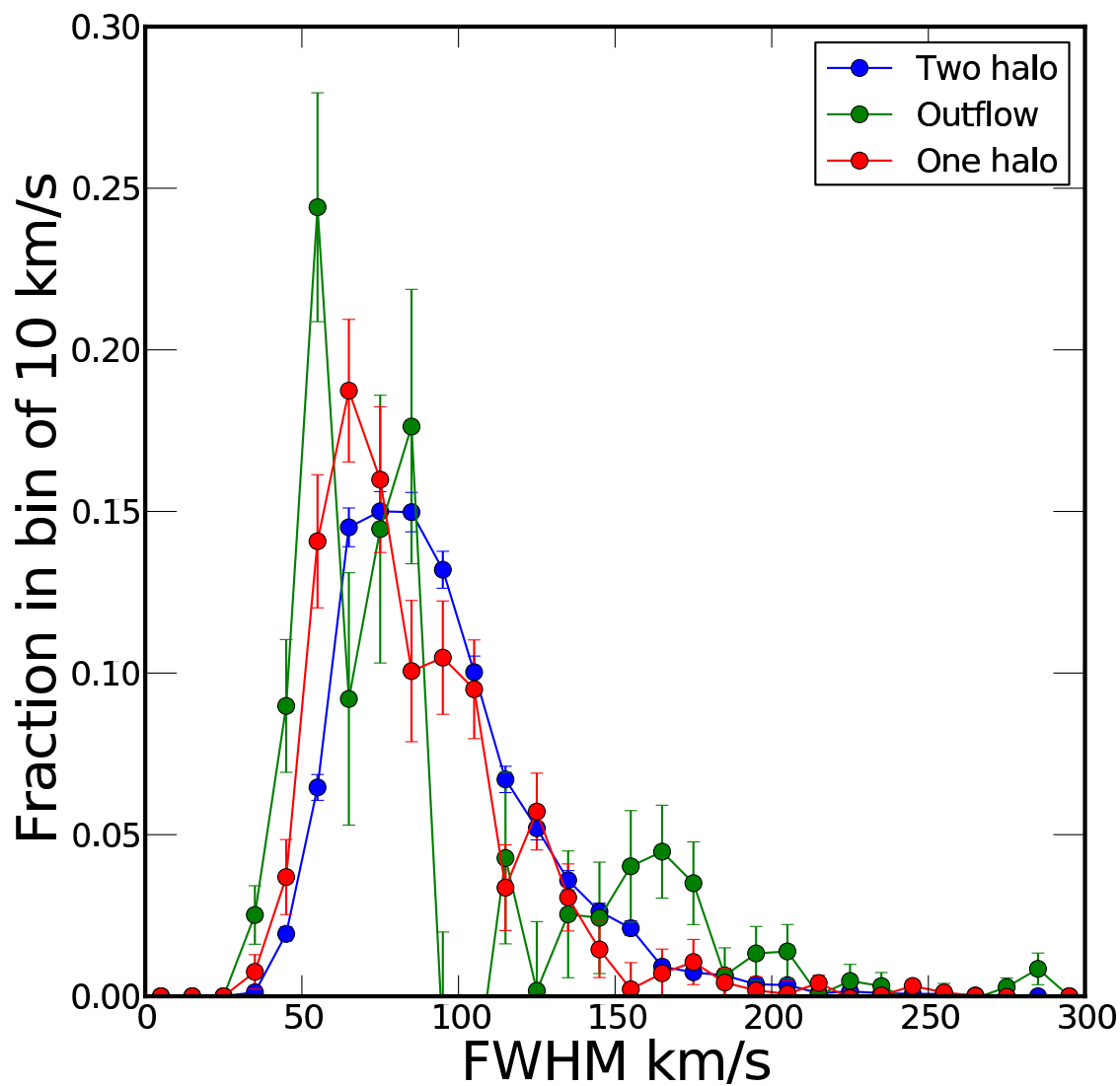


Figure 3.13 Normalized distribution of FWHM for one-halo, outflow and two-halo components. The outflow and one-halo are very anti-correlated which may amplify their difference. It can be inferred that the FWHM for outflows are systematically smaller than other components.

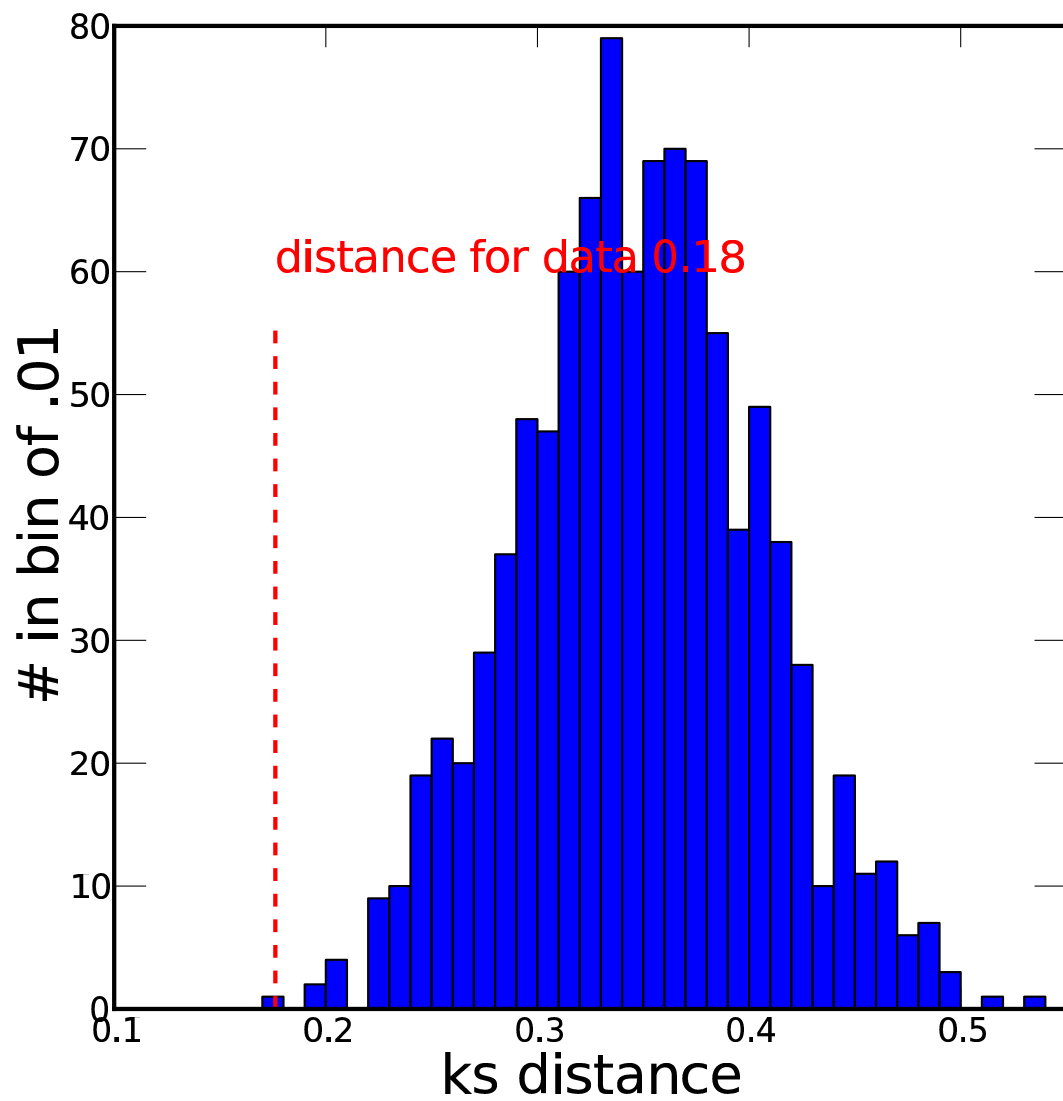


Figure 3.14 The ks-distance of 1000 random realizations of the FWHM distributions of the one-halo and outflow components.

distribution that the two-halo component is steeper compared to the one-halo plus outflow and hence the absorbers in the quasar environment possess systematically larger equivalent width compared to the two-halo term.

Following the steps of the §3.6.3.1, I further explore the difference between the outflow and one-halo components. I estimate the equivalent width distribution for the outflow component from the absorbers in the range  $+0.01 < \beta < +0.04$  subtracting the two-halo component. I determine the distribution for the one-halo component from the absorbers in the range  $-0.01 < \beta < +0.01$  subtracting outflow and two-halo components. Figure 3.16 shows the equivalent width distribution of the two-halo, outflow and one-halo components in blue, green and red respectively. There is no significant difference evident from this plot due to the large error-bars and scatter.

#### 3.6.4 Comparison with other result

There have been various previous studies of narrow C IV absorbers intrinsic to the quasars. These studies try to model the observed number density using very simplistic models. The model adopted in this study is a more physically accurate and statistically consistent way to estimate the outflow component.

Wild et al. (2008) models the expected number density of absorbers by extrapolating the best-fit power-law correlation function, determined in the distance range of 10-100 Mpc, to small (kpc) scales. They find excess absorbers up to 150 Mpc away from the quasar. This, unfortunately, result is not directly comparable to the results of this chapter as they did their analysis in comoving distance space and I choose velocity space of the quasar. The result of their paper that excess of absorbers can not be explained by clustering alone holds true for this study even after using more realistic handling of correlation function scaling to smaller scale. The sample size of their C IV absorbers is 6,459 where as this study uses 7,507 absorbers, however, in this study we remove a large portion of spectrum to make cleaner data.

Nestor et al. (2008) adopted a more detailed model for number density compared to Wild et al. (2008). They modeled the number density of absorbers by adopting an intrinsic

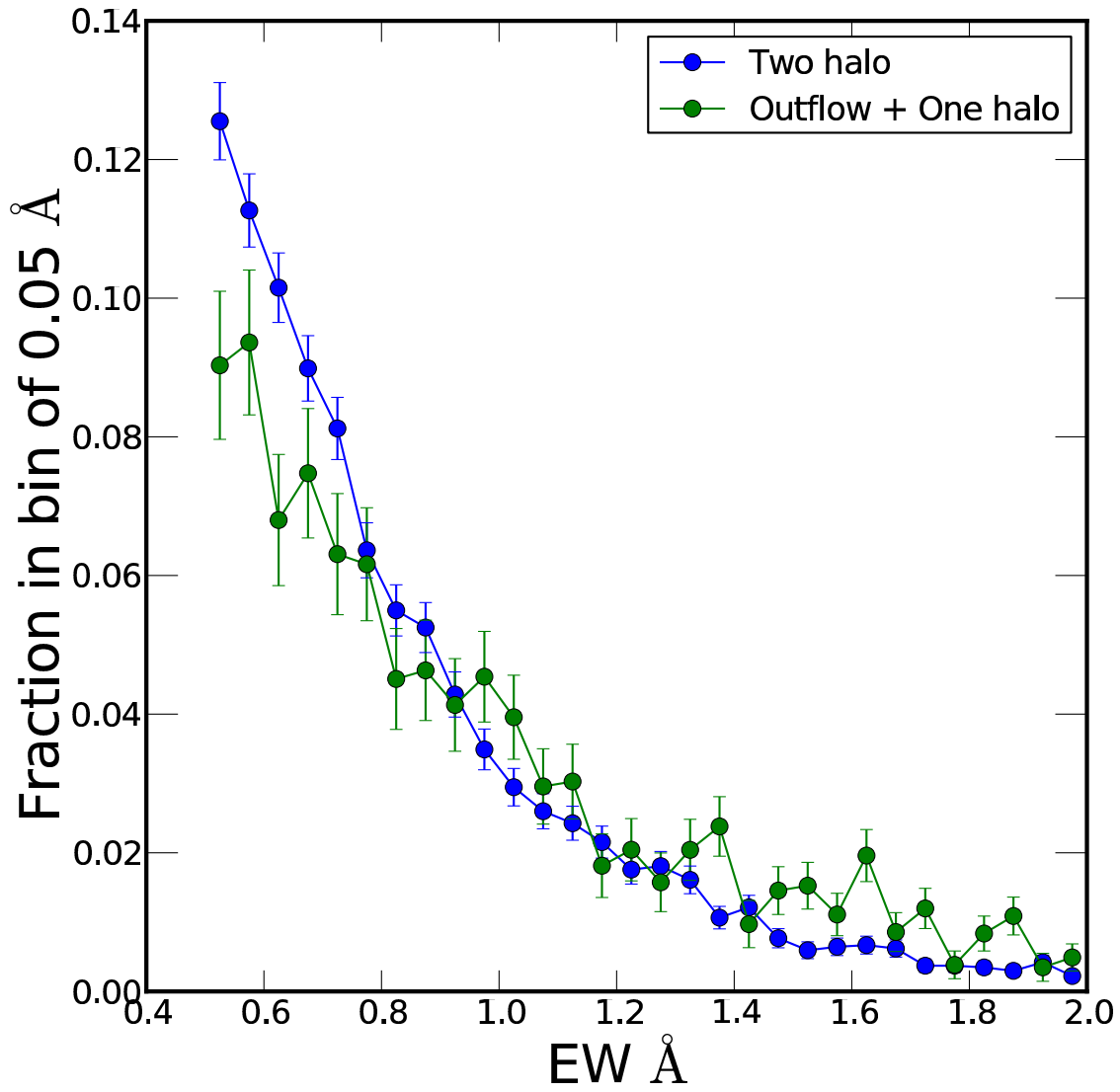


Figure 3.15 Normalized distribution of equivalent width for the two-halo (blue) and one-halo plus outflow (green) CIV absorption systems. The distributions are significantly different and suggest systematically larger equivalent widths for the associated absorbers near quasars.

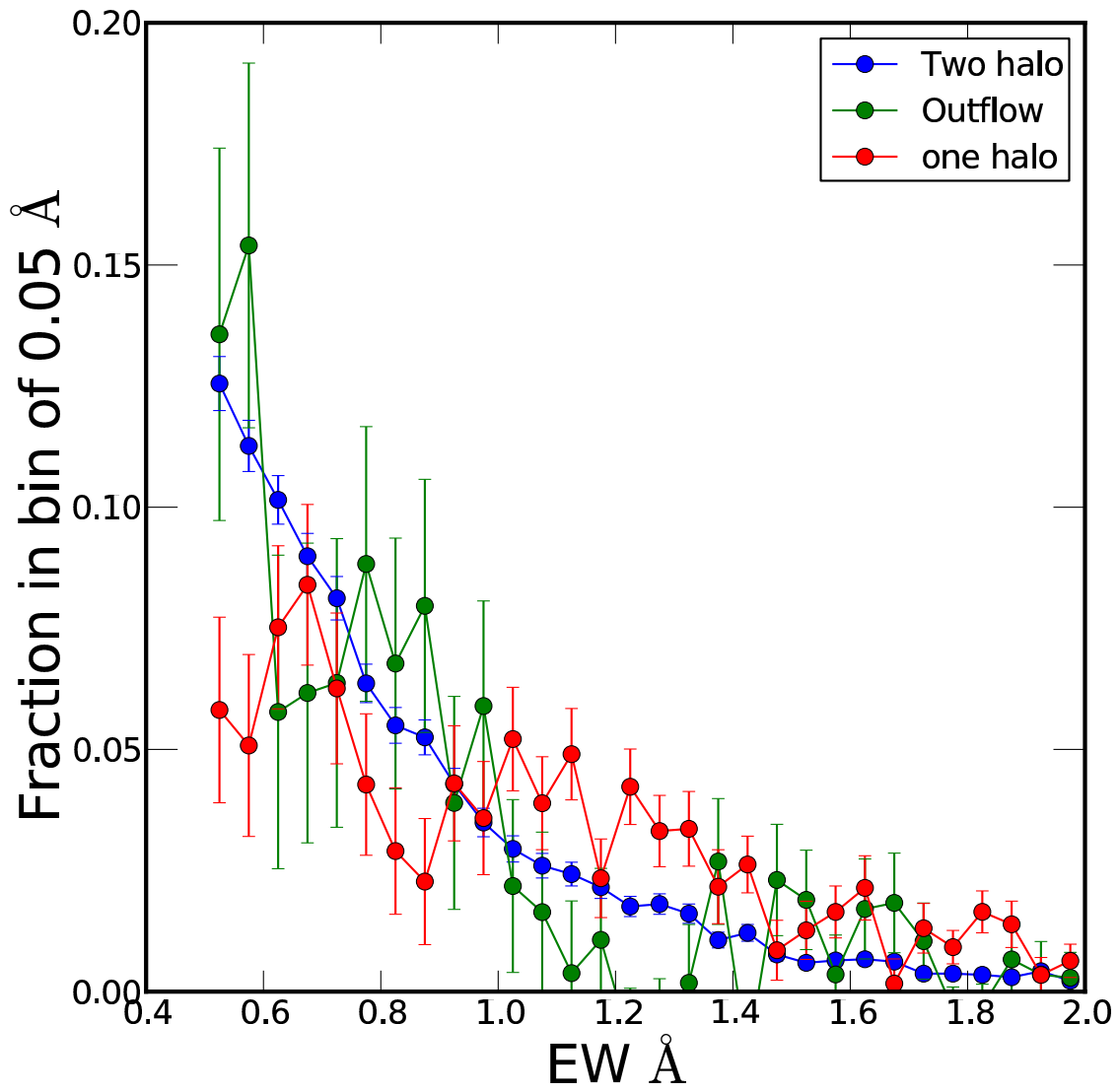


Figure 3.16 Normalized distribution of equivalent width for one-halo, outflow and two-halo components in blue, green and red respectively. No clear inference can be made from this about the distribution of one-halo and outflow components.

term similar to the one-halo model in this chapter and constant term which is similar to two-halo term of this chapter in the limit of large distances from the quasar. They constrained their model from different parts of the velocity space and determined the outflow component by subtracting the best-fit of the model from observed number density. My work improves on this by modeling the two-halo term using halo occupation model formalism and taking proper care of the redshifts of the quasars into account. [Nestor et al. \(2008\)](#) measured the peak fractional contribution of the outflow to be  $\simeq 0.81 \pm 0.13$  at  $v \simeq 2,000 \text{ km s}^{-1}$ . Their results broadly match with the one from this chapter, but here I find the peak to be at  $v \simeq 2,100 \text{ km s}^{-1}$  contributing a smaller fraction ( $\simeq 0.55 \pm .05$ ) of total absorbers. Their result shows a tail of outflow velocity extending to  $v \simeq 12,000 \text{ km s}^{-1}$ . Unlike theirs, I do not find significant contribution of outflow at  $v > 8,000 \text{ km s}^{-1}$ . I believe the difference is due to simplistic model of [Nestor et al. \(2008\)](#) which does not consider the correlation function. Due to the explicit modeling of the outflow component in my work, I believe, the statistical inference of the outflow, is more robust and removes the tail of outflow at higher velocity as they lack statistical significance. This study uses 7,507 C IV absorbers compared to the 2,009 of [Nestor et al. \(2008\)](#). This large sample size enables better constraints of the different components.

### 3.7 SUMMARY AND FUTURE DIRECTION

This study measures the velocity distribution and number density of the C IV absorbers in the outflow of quasars using data from SDSS-III BOSS survey. I focused on the detailed modeling of the number density of the absorbers according to their physical origin and undertook a statistically robust measurement of different components. I conclude the following.

- The observed C IV absorbers can not be explained with the clustering of quasar and C IV systems alone.
- The outflow system contribute  $\simeq 10\%$  of the all C IV absorption systems detected.
- The outflow velocity peaks at  $\simeq 2,100 \text{ km s}^{-1}$  and are insignificant at  $> 8,000 \text{ km s}^{-1}$ .
- Brighter quasars have larger outflow velocities than dimmer ones.

- CIV absorbers affected by quasars have smaller full-width-half-max and larger equivalent widths compared to the ones which are not affected by quasars.

A repeated analysis with the full BOSS sample will have  $\sim 3$  times more absorbers. The statistical advantage of the full BOSS sample will greatly improve our ability to determine the difference of properties (equivalent width, full-width-half-max) between outflowing absorbers and clustering absorbers in the host halos of the absorbers.



## 4.0 SUPERNOVA IA COSMOLOGY AND SYSTEMATICS

Supernova Ia cosmology burst onto the center stage of cosmology when it was used to discovering the acceleration of the expansion of the universe ([Riess et al. 1998](#); [Perlmutter et al. 1999](#)). The next challenge, since the discovery of dark energy, has been to estimate its equation of state,  $w$ , which describes the relation of its pressure to its energy density. The generation of surveys that followed, such as ESSENCE, aimed to measure the  $w$  of dark energy. In addition to estimating the value of  $w$ , it is important to measure the error on it both statistical and systematical.

The new generation of supernova surveys like Pan-STARRS, DES, and LSST will yield a much larger SN Ia sample. These large samples of SN Ia will measure  $w$  with greater precision and will be instrumental in measuring the evolution of  $w$  over cosmic time. However, to reach the full potential of these large samples of SN Ia data, which have the potential to give a much smaller statistical error, we must improve our understanding of systematic errors, as they do not decrease with large sample sizes. Therefore, a good estimation of systematic errors is critical in order to provide a guide to channel the effort to tackle the largest systematic error contributor. All recent SN Ia analysis suggest a high importance to estimating systematic uncertainties ([Conley et al. 2011](#); [Kessler et al. 2009a](#); [Wood-Vasey et al. 2007](#)).

This chapter follows the trend of improving upon the estimation of systematics and applying the improvements to the SN Ia data from the ESSENCE survey. In §4.1, I explain how SN Ia are useful for understanding cosmology. I describe the effect of dust on supernova cosmology in §4.2 and highlight the dependence of the dust uncertainty on the possible progenitors. In §4.3, I describe the origin of the SN Ia data that is being used for the study. I explain the method of fitting the light curves, which is essential to the estimation of intrinsic parameters for the individual supernova, in §4.4. In §4.5, I explain the tool used

to generate the Monte Carlo simulations for the surveys and also explain the properties of the simulation data generated by the tool. §4.6 presents the description of the systematic errors that could be affecting the cosmological inference and the estimation of those errors for our data. Finally, in the last section of this chapter, §4.7, I summarize the conclusions from our study and present future direction for this study.

## 4.1 COSMOLOGY WITH SUPERNOVA IA

In classical physics, we can describe the distance,  $D$ , of a source with intrinsic luminosity,  $L$ , and measured flux,  $F$ , as

$$D = \sqrt{\frac{L}{4\pi F}} \quad (4.1)$$

Since the discovery of the acceleration of the expansion of the universe, requiring a component of universe to have negative pressure, the standard way to describe dark energy is by its equation of state,  $P = w\rho c^2$ . Assuming Einstein's general theory of relativity holds, the "luminosity distance",  $D_l$ , is given by

$$D_l = \frac{(1+z)c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}}} \quad (4.2)$$

where  $\Omega_m$  and  $\Omega_\Lambda$  are the ratios of the densities of matter and dark energy to the critical density of the universe. Here we have assumed the universe to be flat ( $\Omega_\Lambda = 1 - \Omega_m$ ). Using the luminosity distance, we can write the distance modulus as follows

$$\mu \equiv m - M = 5 \log D_l - 5 \quad (4.3)$$

where  $m$  is the apparent magnitude, which is a measure of flux, and  $M$  is the absolute magnitude, which is a measure of luminosity, and  $D_l$  is luminosity distance in units of parsecs. Standard candles have the same luminosity, making the absolute magnitude a constant for all SN Ia observation. We can use Eq. 4.3 to constrain the cosmological parameters  $\Omega_m$  and  $w$  if we have a sufficiently large number of supernovae Ia with well-measured apparent magnitude and redshift.

As mentioned in §1.4.1, the supernova Ia’s “standardness” can be improved by using the brighter-slower and brighter-bluer correlations. Using these correlations, Eq. 4.3 can be modified as follows

$$\mu \equiv m - (M - \alpha \text{ shape} + \beta \text{ color}) \quad (4.4)$$

where  $\alpha$  and  $\beta$  are the global correlations of brightness-slowness and brightness-color, and shape and color are parameters describing the slowness and color of the individual supernova Ia light curves.

## 4.2 DUST EXTINCTION AND THE RELATIONSHIP BETWEEN DUST AND SN IA PROGENITORS

One of the largest sources of uncertainty is the lack of understanding of dust in the host galaxies of supernovae and their local environments. The estimation from the most studied supernovae suggests steeper dependence of extinction versus wavelength with typical  $R_V$  values of  $\approx 2$  (Wang 2005; Krisciunas et al. 2007), compared to  $R_V = 3.1$  as observed for the Milky Way galaxy (Schlegel et al. 1998).

The source of dust extinction can be divided into two components: 1) dust from the host galaxy; 2) dust from the local environment of the progenitor. The dust due to the host galaxy would not depend on the progenitor of the supernova, but the local environment dust could be highly correlated with the type of progenitor. In the single degenerate model, the progenitor accretes from a companion through Roche-lobe overflow and is likely to exhibit a small explosion before the supernova (Nomoto 1982). Such small explosions or a series of them can create dust clouds around the progenitor (Corradi 2003; Bujarrabal et al. 2010). These progenitors also reside in star-forming regions of the galaxies, which are inherently dusty environments. For these reasons, the single degenerate progenitors are expected to be in environments with more dust extinction. In the case of the double degenerate progenitor, the binary system is composed of two degenerate cores, meaning that star formation would have ceased a long time before, so they are expected to be located in less dusty environments. They would still, however, suffer from dust extinction due to the dust in the host galaxy.

The canonical value of  $R_V$  in Milky Way is 3.1, but it ranges from 2-6 along different line of sight (Schlegel et al. 1998). In a region of dense star formation,  $R_V$  can be as small as  $\approx 2$  (Martin et al. 1989; Larson et al. 1996; Gordon and Clayton 1998; Larson et al. 2000; Clayton et al. 2003; Gordon et al. 2003).

The treatment of host galaxy extinctions is very important for supernova cosmology. IT is treated several different ways in the literature: 1) assume the  $A_V$  to be linear with flat prior (Perlmutter et al. 1999; Knop et al. 2003); 2) use models of the dust distribution (Hatano et al. 1998; Commins 2004; Riello and Patat 2005) in galaxies to model line of sight extinction values (Riess et al. 1998; Perlmutter et al. 1999; Tonry et al. 2003; Riess et al. 2004); 3) assume that the distribution of host galaxy  $A_V$  is of exponential form (Jha et al. 2007); 4) use self-calibration within a set of low- $z$  supernovae to obtain a color versus  $A_V$  relationship and assume the relation for the full set (Astier et al. 2006). Different assumptions have different strength and weaknesses. The flat prior assumption assumes the least amount of knowledge about the extinction, but it also allows the unphysical value of negative  $A_V$ . The method of modeling the dust distribution is physically motivated, but it relies on the accuracy of our understanding of the complicated process of dust formation. The Jha et al. (2007) derivation of the  $A_V$  distribution assumes a particular distribution of color, and the highly extinguished objects often affect the fit of the overall dust law, even though they may represent a separate population.

## 4.3 SUPERNOVA DATA FOR THIS STUDY

### 4.3.1 ESSENCE Supernova Survey

Designing surveys to look for supernova Ia is a difficult challenge because supernovae occur only a few times per millennium in a typical galaxy, which makes, concentrating on a few galaxies inefficient. Supernovae are transient events that last for only a couple of months. A possible observation strategy could be taking images of large part of the sky regularly, so that a new bright spot in the image could be identified. This strategy would give candidates

for supernova Ia that would need to be watched more carefully in order to be identified as real SN Ia.

**Equation of State: SupErNovae trace Cosmic Expansion Survey (ESSENCE)** was a ground-based multi-year project aimed to identify the supernova Ia in the redshift range of  $0.2 < z \leq 0.8$ . The survey was conducted using the Blanco 4m telescope at Cerro Tololo Inter-American Observatory (CTIO) located in Chile. It used passbands with a MOSAIC wide-field CCD camera. The survey took repeated images in R and I passbands with a cadence of a few days separation for three consecutive months each year. The base bands, R and I, were chosen to coincide, at a redshift of  $z \sim 0.5$ , with the rest frame bands, B and V, where our understanding of SN Ia is best. When the survey identified a potential supernova Ia, several different large aperture telescopes (Keck, VLT, Magellan, Gemini) followed up on the object. Taking spectra from large telescopes helped to identify the type of supernova and also gave accurate measurements of the redshift of the supernova.

The goal of the survey is to put tight constraints on the equation of state of dark energy,  $w$ . The ESSENCE survey was designed to take advantage of the uniformity of photometry because it used a single telescope and instrument throughout the survey period. The survey also focused on the sources of systematic errors that are now a bigger source of uncertainty than the statistical error associated with the small number of supernova Ia observations. The survey collected data for 197 half nights over a six year period of observation. The survey confirmed 203 supernova Ia during the entire observation period. The detail of the design of the ESSENCE survey is elaborated in [Miknaitis et al. \(2007\)](#).

[Wood-Vasey et al. \(2007\)](#) have done the cosmological analysis using three years of data from ESSENCE. They explore, in great detail, the systematic error for the analysis and their estimation. Table 5 in that paper, lists all the individual systematics considered and estimations of the effect on  $w$ .

#### 4.3.2 Low redshift sample

To a large extent our understanding about SN Ia comes from the well-observed sample of low redshift,. They have been observed at densely sampled epochs in multiple pass-bands.

Understanding the low redshift sample enables us to produce light curves for the high redshift SN Ia, correcting for extinction and incorporating the brightness-color and brightness-shape correlations. The low redshift sample comes from various sources including the: Calán/Tololo survey (Hamuy et al. 1996), CfAI (Riess et al. 1999), CfAII (Jha et al. 2006). The sources are compiled in Jha et al. (2007) with much emphasis on making the measurements as accurate as possible. I use this sample of 125 nearby SN Ia for our study. In addition to light curve measurements, the low redshift sample is also very important for cosmological analysis, as our goal in this study is to obtain the tightest constraint on  $w$ . The absolute distances of the supernovae depend on the parameter  $w$  and the Hubble parameter  $h$ . However, since the ratio of the distances of high-redshift supernovae to low-redshift supernovae is independent of the Hubble parameter  $h$ , hence the low-redshift supernovae sample enables us to make more robust constraints on  $w$ , by not being dependent on absolute knowledge of  $h$  and the luminosity of SN Ia.

### 4.3.3 Other Surveys

SN Ia surveys yield a limited number of events during the survey lifetimes. Using events from different surveys for analysis is an easy way to improve the sample size. In addition to having better statistics, using various surveys has the benefit of sampling different redshift ranges, which will produce better constraints on the cosmological parameter. In this study, we include data from SDSS (Kessler et al. 2009a, 115 SN Ia), SNLS (Astier et al. 2006, 65 SN Ia), and HST (Riess et al. 2007, 20 SN Ia).

## 4.4 LIGHT CURVE ESTIMATOR

SN Ia exhibit variability in light curve shape, colors, intrinsic luminosity, and spectral features. These properties are measured in the observer reference frame using photometry at non-periodic intervals using various filters. The redshifting of the spectra makes different parts of rest-frame spectra available for measurement. Apart from intrinsic variability of the

SN Ia spectrum, the difference in dust absorption along different lines of sight affects the observed properties of SN Ia. Converting observed properties of SN Ia to the rest-frame properties of interest is a non-trivial task but of central importance to analysis. Many such light curve estimators have been developed, e.g. MLCS2k2 (Jha et al. 2007), SALT II (Guy et al. 2007), BayeSN Mandel et al. (2011). In this study, we are using the SALT II light curve estimator.

#### 4.4.1 SALT II

SALT II models the mean evolution of the spectral energy distribution sequence of supernovae Ia and the variation with a few dominant components. It also allows a time independent variation with color. The following functional form of flux,  $F$ , is assumed:

$$F(SN, p, \lambda) = x_o [M_o(p, \lambda) + x_1 M_1(p, \lambda) + \dots] \exp [c \text{ CL}(\lambda)] \quad (4.5)$$

where  $p$  is time in the rest-frame since the date of maximum luminosity in B-band, and  $\lambda$  is the rest-frame wavelength of the supernova.  $M_o(p, \lambda)$  is the average spectral sequence;  $M_k(p, \lambda)$ , for  $k > 0$ , represents additional components that describe the main variability of supernova Ia;  $\text{CL}(\lambda)$  represents the average color correction law; and  $c$  is defined as  $(B - V)_{\text{max}} - \langle B - V \rangle$ . Therefore,  $x_k$  and  $c$  are individual supernova Ia parameters and  $M_k$  is a global parameter.

SALT II uses multi-band light curves to train the model. It also uses the spectroscopic data to improve the model resolution in wavelength space. Use of spectroscopic information enables the K-correction to be treated in a consistent manner.

The above model is constructed using the nearby supernova Ia sample and the high redshift supernovae from the Supernova Legacy Survey (Astier et al. 2006; Conley et al. 2011). Including the high redshift supernova Ia enables us to constrain the model in the wavelength range of the U-band, which can not be done using only nearby supernovae Ia because they have poor U-band data due to the opacity of Earth's atmosphere in the ultraviolet. Using these datasets the model from Eq. 4.5, is constrained at grid points in phase,  $p$ , and wavelength.

Once the training of the model is completed, SALT II can be used to evaluate the light curve of any supernova Ia by trying to evaluate the best fit for variability parameters  $x_k$  and  $c$ . The model should, therefore, be able to produce the light curve for any supernova Ia. Using the parameters of SALT II, Eq. 4.4 would be written as

$$\mu \equiv m - M + \alpha x_1 - \beta c \quad (4.6)$$

## 4.5 MONTE CARLO SIMULATION

Systematic studies on combined SN Ia samples can be done, in principle, by selecting subsets of whole datasets, according to different properties, and doing complete analysis on the different subsets. However, this would require a vary large dataset so meaningful constraints on the subset could be found. The current worldwide SN Ia sample is far from reaching the required size ( $>10,000$ ) for such analysis, but the problem can be overcome if we are able to create a simulated dataset that takes into account the effect of different parameters on the dataset. Although simulated data is not useful for finding new systematics in the data, it can accurately measure the existing systematic errors for any parameter modeled in the simulated dataset.

### 4.5.1 SNANA

SNANA is a publicly available simulation tool designed to model SN Ia datasets. The software is described in [Kessler et al. \(2009b\)](#). The software contains a Monte Carlo simulator, a light curve fitter, and a cosmology fitter. The software is designed to use multiple SN Ia light curve models and can be easily extended to include new models of light curve fitting.

SNANA provides the ability to specify the description of any survey, such as the MJD of survey observations, filters, and many other properties, which enables the Monte Carlo simulator to generate supernova datasets closely following the real data properties. SNANA also provides a way to specify the desired properties and the model used for light curve fitting. These properties include, but are not limited to, specifying the brightness-shape correlation,



brightness-color correlation, dust extinction distribution and various other model parameter distributions that could affect the distribution of the supernova Ia data. The software also has the capability to specify a quality cut on the supernova data before it is accepted as a reliable supernova observation. To model an individual survey, we can use the specific filters and the quality based on the filters and actual observational conditions.

The SNANA software provides several light curve fitter options, including SALT II and MLCS2k2, and provides an easy way to support new light curve models. These options help to achieve some uniformity in the light curve model, making it easy to test the robustness of the analysis. The light curve fitter provides various methods to obtain the best fit value of the parameters and produces the measurements of different parameters of individual supernova.

The software also provides a cosmology fitter that takes the output of the light curve fitting and attempts to fit the global parameters, which could be the cosmological parameter or the global brightness-shape or brightness-color correlation. All of these parameters are provided in the simulation step, so we can check if there is a bias introduced by the analysis.

There are many other capabilities of the SNANA tool, but I have only outlined those that are used by our analysis.

#### **4.5.2 Simulation data**

I created the simulation dataset to closely follow the characteristics and composition of the real dataset, so the simulated data is an accurate representation of the real dataset. I used the SNANA software described in section 4.5.1 to make one hundred realizations of the dataset. The real dataset consists of a collection of surveys. To imitate the real data, I generated simulated data for the LOWZ, SDSS, ESSENCE, SNLS, and HST surveys, having 125, 115, 150, 65, and 20 supernovae respectively. I used custom survey definition files to generate appropriate datasets for each survey and then added the simulated data to make the complete simulated dataset used for analysis. I generated all the simulated data using the SALT II model. After the SN Ia data was generated, I concatenated the data from different surveys to make the complete dataset representing the real data. I used the light curve fitter on the simulated dataset to measure the properties of the individual light curves.

I then used the cosmological fitter to get the best fit cosmological parameters, assuming a flat universe.

## 4.6 SYSTEMATIC UNCERTAINTIES OF THE SUPERNOVA ANALYSIS

In this section, I aim to estimate the errors due to the systematics that affect this analysis. I first make a list of possible systematic error sources and then predict how they could be affecting our data in section 4.6.1. In section 4.6.2, I describe the methodology I used to find the probability distribution of the error introduced by any specific systematic error. In section 4.6.3, I describe the analysis of the systematic error for our data sample using the methodology described in section 4.6.2.

### 4.6.1 List of systematic uncertainties

In this section, I mention and explain various systematic errors that could affect the inference of cosmological parameters.

1. **Dust and Milky Way Extinction:** Supernovae Ia are important to cosmology because they are standard candles. However, their observed brightness can be affected by material, such as dust, that lies between the supernova and us. While the intergalactic medium is quite thin and does not contain much dust that would affect the brightness, our own Milky Way galaxy contains a significant amount of dust. The host galaxies of supernovae can also contain a significant amount of dust. Our ability to determine the absolute brightness relies on our ability to correctly estimate the dimming of brightness due to dust. Dust extinction affects smaller wavelengths more than larger wavelengths, so the net affect of dust extinction is to make the supernova appear redder. The availability of multi-band photometry data enables us to determine the color of high redshift supernova. Each supernova may be expected to have a different dust extinction, due to environment effects, however, it is not possible to correct for the effect of dust extinction using only color information. Estimation of the global distribution of dust extinction

is used to correct the individual supernova color. The well-observed nearby sample of supernovae provides the distribution of supernovae in color space. Assuming the distribution of the nearby sample to be true at higher redshifts, we can estimate the global extinction distribution of the supernova sample. Any error in estimating the global dust extinction affects the estimation of all supernova colors individually. The inference of cosmological parameters is affected systematically.

2. **Evolution of Dust Extinction:** The extinction of supernovae Ia due to dust in the host galaxies is not very well understood. There are reasons to think that there could be evolution of dust in the host galaxies of supernovae Ia (Totani and Kobayashi 1999; Jain and Ralston 2006), as the galaxies evolve with redshift affecting the dust content due to various factors (e.g., star-formation, metallicity). Our measurement of dust extinction is not accurate enough to measure the redshift evolution of dust extinction. The assumption of no evolution in dust extinction can lead to a systematic error dependent on redshift.
3. **Photometric Zeropoint:** In astronomy, the prevalent way of measuring the flux is using the magnitude system. The magnitude is defined as

$$m = -2.5 \log(F) + \text{zeropoint} \quad (4.7)$$

where  $F$  is flux in unit of ergs per second per  $\text{cm}^2$  per Hz. The zeropoint and  $m$  have the same unit of “mag”. Since every telescope and instrument has unique characteristic behaviors, the zeropoint offset has to be calculated for each telescope, instrument, and filter. Any systematic error in estimating the zeropoint for each filter will affect the magnitude estimation for that pass-band data for all observations. These errors in zeropoint offsets affect the supernova Ia data in following ways:

- I) Cosmological analysis of supernovae Ia depends heavily on observations of low redshift supernovae Ia. As explained in section 4.4.1, the local supernova Ia are used to train the light curve fitter and the result is used to estimate the light curve for high redshift supernova Ia. These samples of local supernova Ia were observed from multiple telescopes, using different instruments and various filters. The error in photometric calibration would introduce systematic errors in training the light

curve fitter and thus would affect the determined properties (i.e., stretch, color) of all the supernova Ia.

- II) For the high redshift supernova survey (e.g., ESSENCE), a precise zeropoint estimation for each different filter is also very important. Since the errors in zeropoint offset for different filters are independent of one another, the errors could potentially cause large errors in color. This color error will affect all the supernova Ia from the survey. From Eq. 4.5, we can see that the color term is important to the training process and, in conjunction with color correction law, will systematically cause under- or over-estimation of the extinction, affecting the estimation of cosmological parameters.

4. **Local flow:** Supernova cosmology studies compare the low-redshift supernovae with a high-redshift sample. The goal is to deduce the expansion history of the universe at different redshifts. An implicit assumption used in this analysis is that the observed supernova redshift is only due to the expansion of the universe. Because the redshift measures the recession velocity, which is due to Hubble flow as well as peculiar velocity of supernova in their local environment, the assumption is not strictly true. However, for supernovae separated by large cosmological distances, the peculiar velocity cancels out, as the directions are randomly distributed and do not induce bias in the measurements. The low-redshift supernovae are not separated by large cosmological distances, so the peculiar velocities could be correlated, and the net affect of having many supernovae could be a nonzero peculiar velocity in the direction of the coherent motion of the local universe. Such a residual will induce systematic error in the estimated expansion history and will lead to incorrect inference of cosmological parameters. We currently do not have precise information about the local flow, so to avoid introducing error due to local flow, we need to remove some very nearby supernova from the sample.

5. **Malmquist Bias:** The Malmquist bias is the selection bias in a magnitude limited survey where we selectively intrinsically brighter objects at large distance. As a result, the properties of that sample that correlate with intrinsic brightness would also correlate with redshift, even if there is no intrinsic evolution of that property with redshift. This selection effect is enhanced because spectroscopic criteria are generally more stringent;

a faint supernova Ia may be too faint to take a clean spectra. This selection effect can interfere with cosmological analysis in a few possible ways. Error in the measurement of the strength of the shape-luminosity correlation is one possibility. For a given shape of supernovae Ia, the selection effect would tend to choose the brighter supernovae Ia, increasing the inferred shape-luminosity correlation. This mis-estimation will affect all the supernova Ia in the sample.

Another way the Malmquist bias could affect the cosmological inference is by inducing errors in the dust extinction of the supernova Ia. For any given intrinsic brightness of supernova Ia, the selection effect will remove the supernova Ia with more dust extinction and affect our estimation of dust extinction in the sample. The mis-estimation would not be so bad, as it will be a true representation of the sample; however, selection effects introduce a redshift dependence and produce a relative systematic error in high redshift supernova Ia.

6. **Rest Frame U/u Band:** The rest frame U-band data for nearby supernovae Ia are almost the same as the observer frame U-band data. Since the Earth's atmosphere is not completely transparent for U-band wavelength, our U-band data for nearby supernovae is of poor quality and difficult to calibrate. For high redshift supernovae Ia the rest frame U-band is redshifted to optical range, so they are well observed. Compared to rest frame U-band observation of high redshift supernovae Ia, the nearby sample has a big offset due to unreliable U-band data. Since training the light curve fitter is largely dependent on the nearby supernovae Ia observations, the problematic U-band data can inflict systematic errors on the light curve estimation of all supernovae Ia, which affects the cosmological parameter estimation. The U-band measurements also exhibit a larger dispersion and are inherently less standardizable, compared to other bands.
7. **Intrinsic Brightness Evolution:** Supernovae Ia are standardizable candles within some accuracy. However, the possibility exists that supernovae Ia brightness evolves with redshift. The studies looking to find such evidence have not able to find any, but a weak evolution of brightness, at the level of a few percent, can not be ruled out. Such error will place a redshift dependent error on the distance modulus of the supernovae Ia and will systematically bias the cosmological parameter estimated from the analysis.

### 4.6.2 Methodology

In this section, I describe the generic methodology I have used to estimate the systematic errors. I describe use the SNANA monte carlo simulation tool, described in section 4.5.1, to model the systematic errors. For any given cosmological parameter  $X(p_1, p_2, \dots, p_n)$  where  $p_k$  is  $k^{th}$  systematic parameter, the systematic errors on  $X$  can be written as

$$\delta X_{\text{sys}}^2 = \sum_k \left( \frac{\partial X}{\partial p_k} \right)^2 \delta p_k^2 \quad (4.8)$$

I assume here that the different parameters are not correlated with each other and can be estimated independently. To estimate  $\frac{\partial X}{\partial p_i}$ , I generate a random realization of our final supernovae Ia data from various surveys using SNANA and using  $p_i = p_{i,\text{True}}$ . I complete the analysis of this dataset by using a light curve fitter and a cosmological fitter, using the same parameter as in the simulation, and get the best fit value for  $X$  to be  $x_{i,\text{True}}$ . I redo the above analysis now assuming that I have mis-estimated parameter  $p_i$  to be  $p_{i,\text{True}+\Delta}$  and get the cosmological parameter  $X$  to be  $x_{i,\text{True}+\Delta}$ . Using the above information, I can write

$$\frac{\partial X}{\partial p_i}(p_i = p_{i,\text{True}}) \simeq \frac{x_{i,\text{True}+\Delta} - x_{i,\text{True}}}{\Delta} \quad (4.9)$$

The estimation of  $\frac{\partial X}{\partial p_i}$  is only for one random realization. Our dataset sample is only one realization of an infinite number of possible outcomes for any give set of parameters. To completely characterize  $\frac{\partial X}{\partial p_i}$ , I need to find the probability distribution function of  $\frac{\partial X}{\partial p_i}$ . To do so, I repeat the process, with different seed values, 100 times for any given parameter analysis. The distribution  $\frac{\partial X}{\partial p_i}$  is then converted to a probability distribution function using kernel density estimation. The estimated error on the cosmological parameter  $X$  due to systematic  $p_i$  can be written as

$$\delta X_{\text{sys},i}^2 = \left( \left\langle \frac{\partial X}{\partial p_i} \right\rangle \right)^2 \delta p_i^2 \quad (4.10)$$

### 4.6.3 Analysis

In this section, I present the results of the analysis of some of the systematic errors discussed in §4.6.1. As mentioned in section 4.3.1, the main goal of the ESSENCE survey is to constrain the dark energy equation-of-state parameter. I consider here the systematic error analysis, one systematic at a time.

1. **Dust and Milky Way Extinction:** I estimate here the systematic error due to mis-estimation of the dust extinction parameter  $\beta$  for SALT II (see Eq. 4.6). The current estimated value of  $\beta$  for the nearby sample is  $\approx 2.6$  (Hicken et al. 2009; Kessler et al. 2009a). I estimate  $\langle \frac{\partial w}{\partial \beta} \rangle$  by following the process outlined in section 4.6.2. I first generate a simulation of our dataset using SNANA with  $\beta_{\text{sim}} = 2.6$ . Using the simulated survey dataset, I use the SALT II light curve fitter to estimate the light curve. I then fit for the cosmological parameters by fixing the extinction parameter  $\beta$  to  $\beta_{\text{sim}} + \Delta\beta$ ,  $\beta_{\text{sim}}$ ,  $\beta_{\text{sim}} - \Delta\beta$ , where I choose  $\Delta\beta$  to be 0.2. Using the estimated  $w$ , I calculate the change in estimation of  $w$ ,  $\Delta w$ , for the change of  $\Delta\beta$ , which leads to an estimation of  $\partial w / \partial \beta$ . I also calculate the change in the estimated  $\Omega_m$  as indicated by  $\Delta\Omega_m$ . To estimate  $\partial w / \partial \beta$  across the relevant range of  $\beta$ , I repeat this process for simulations with  $\beta = 1.6, 3.6$ . To estimate  $\langle \partial w / \partial \beta \rangle$  from  $\partial w / \partial \beta$ , I repeat the process outlined above 100 times, in order to estimate the probability distribution function of  $\partial w / \partial \beta$ .

Figure 4.1 shows the  $\Delta w$  and  $\Delta\Omega_m$  for simulations of  $\beta = 1.6, 2.6, 3.6$ . The distribution of points aligned on negatively sloped straight line indicates the line of degeneracy in the  $w$  and  $\Omega_m$  plane, as a more negative value of  $w$  would tend to accelerate the expansion of the universe while a more positive value of  $\Omega_m$  would decelerate the expansion (for a flat universe). The subplots show the difference in distribution for  $\Delta w$  and  $\Delta\Omega_m$  for different  $\beta$ . The plot explains the need to estimate  $\partial w / \partial \beta$  at three different  $\beta$  values in order to be representative of the full range of  $\beta$ . A closer look at the plot reveals that for the lower extinction simulation, the distribution of  $\Delta w$  peaks closer to near zero compared to the higher extinction simulations. This confirms that smaller extinction data suffer less systematic extinction error due to mis-estimation of  $\beta$ .

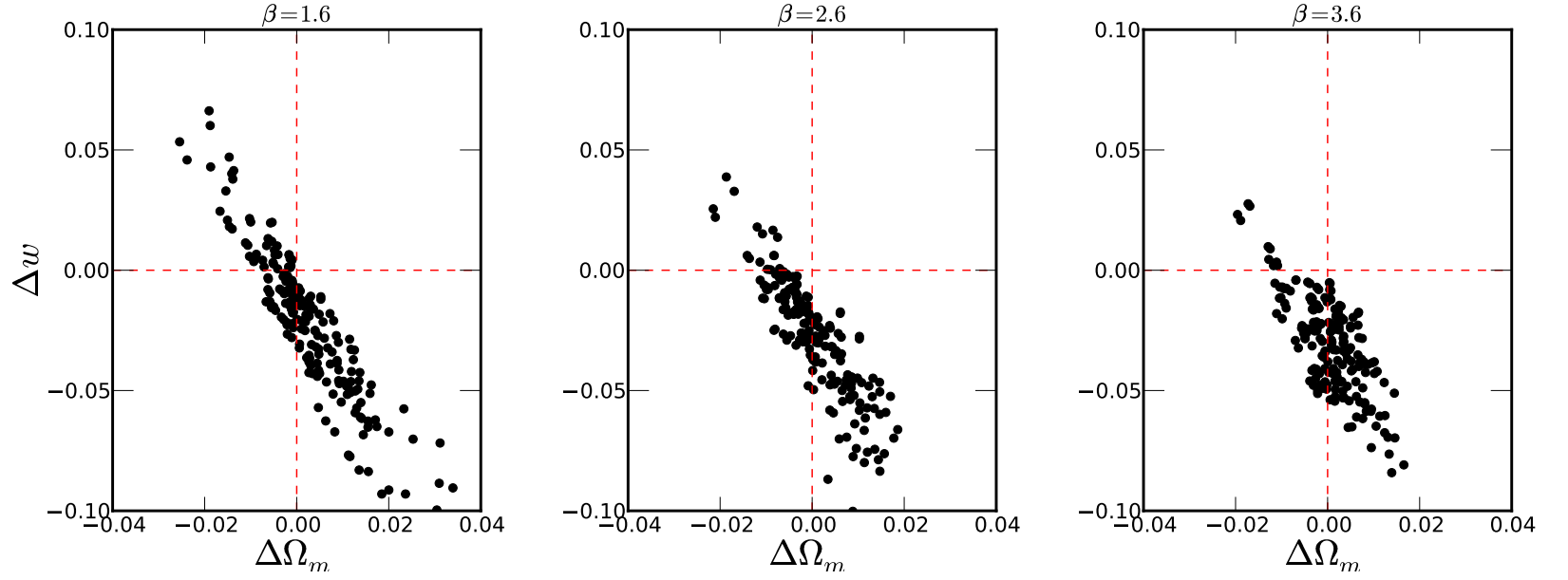


Figure 4.1  $\Delta w$  and  $\Delta\Omega_m$  for  $\Delta\beta = 0.2$  for simulated dataset for assumed  $\beta = 1.6, 2.6, 3.6$ . The plot show the degeneracy in the  $w$  and  $\Omega_m$  plane. The three panels show the difference in distribution of  $\Delta w$  and  $\Delta\Omega_m$  for different  $\beta$  and emphasize the need to estimate  $\partial w / \partial \beta$  for more than one value of  $\beta$ .



Figure 4.2 shows the probability distribution function for  $\partial w/\partial\beta$  estimated from the 100 different  $\partial w/\partial\beta$  estimations. The distribution is estimated using a kernel density estimator. The method involves convolving a Gaussian function with the histogram of measurement to get a continuous and smooth probability density function.

Using the distribution, I estimate  $\langle \frac{\partial w}{\partial\beta} \rangle = -0.132$ . There have been a few studies of dust extinction that estimated the error on the dust extinction parameter for SALT II. Kessler et al. (2009a) find  $\sigma_{R_V} = 0.5$ . Here I conservatively assume the error estimation of  $\sigma_\beta = 1.0$  to be on conservative side. I calculate the systematic error due to dust extinction to be

$$\delta w = \sqrt{\left(\left\langle \frac{\partial w}{\partial\beta} \right\rangle\right)^2} \delta\beta = 0.13$$

The most recent systematic error study from Conley et al. (2011) estimated the systematic error on  $w$  due to dust extinction to be  $\sigma_w \sim 0.01$ . Due to the difference in analysis the errors are not exactly comparable. However, I believe the difference is due to our liberal assumption of error on the dust extinction and due to Conley et al. (2011) having cleaner data with more passbands and excluding highly reddened SN Ia.

2. **Photometric Zeropoint:** Here I try to demonstrate and quantify the systematic error due to zeropoint offsets for the ESSENCE data. ESSENCE data are taken in two passbands, R and I. As mentioned in section 4.6.1, the zeropoint estimate for each band is independent of the other. The systematic error then involves two parameters. I do the joint analysis of these two parameters. I explore the zeropoint estimate error in the range of  $[-.1, .1]$  in 11 bins for both the R and I bands. For each bin I generate 100 realizations of data and complete the cosmological analysis. Figure 4.3 shows the equation of state parameter  $w$  for an induced zeropoint offset in R and I band. The horizontal axis shows the offset in the R band and the vertical axis shows the offset in the I band. The color in any bin represents the derived value of  $w$ . The color-bar shows the mapping between the value of  $w$  and color. This plot shows the amount of systematic error in  $w$  due to zeropoints offsets. It also shows that if both bands suffer from the same error, then they cancel each other when estimating color and produce the correct  $w$ .

Figure 4.4a and 4.4b show the probability distribution function for  $\frac{\partial w}{\partial\Delta R \text{ or } \Delta I}$  for the shift of 0.02 mag. The probability distribution is estimated using a kernel density

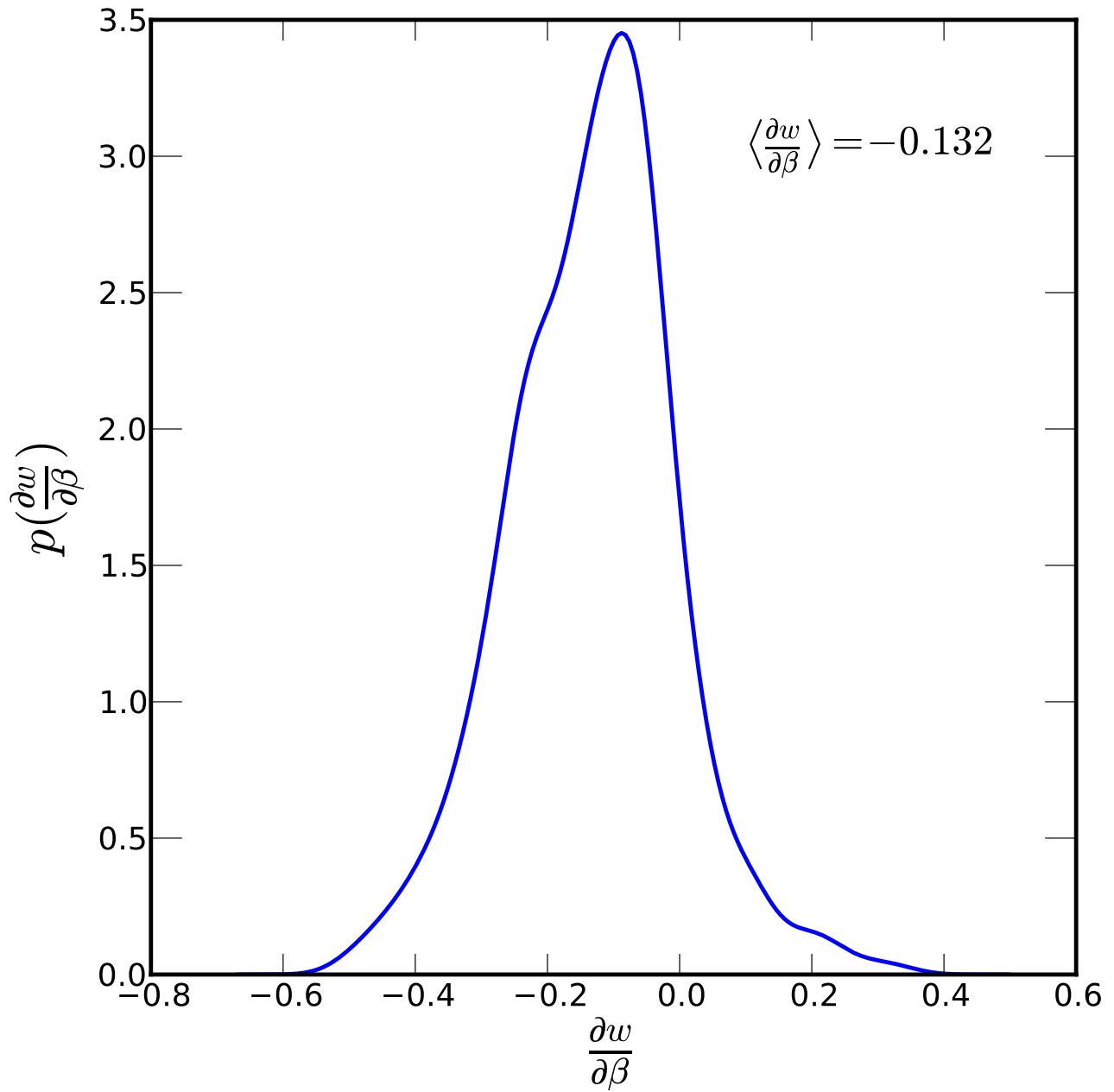


Figure 4.2 Shows the probability distribution function of  $\partial w/\partial \beta$  estimated from 100 simulation to estimate  $\partial w/\partial \beta$ . I estimate  $\langle \frac{\partial w}{\partial \beta} \rangle$  from this distribution.

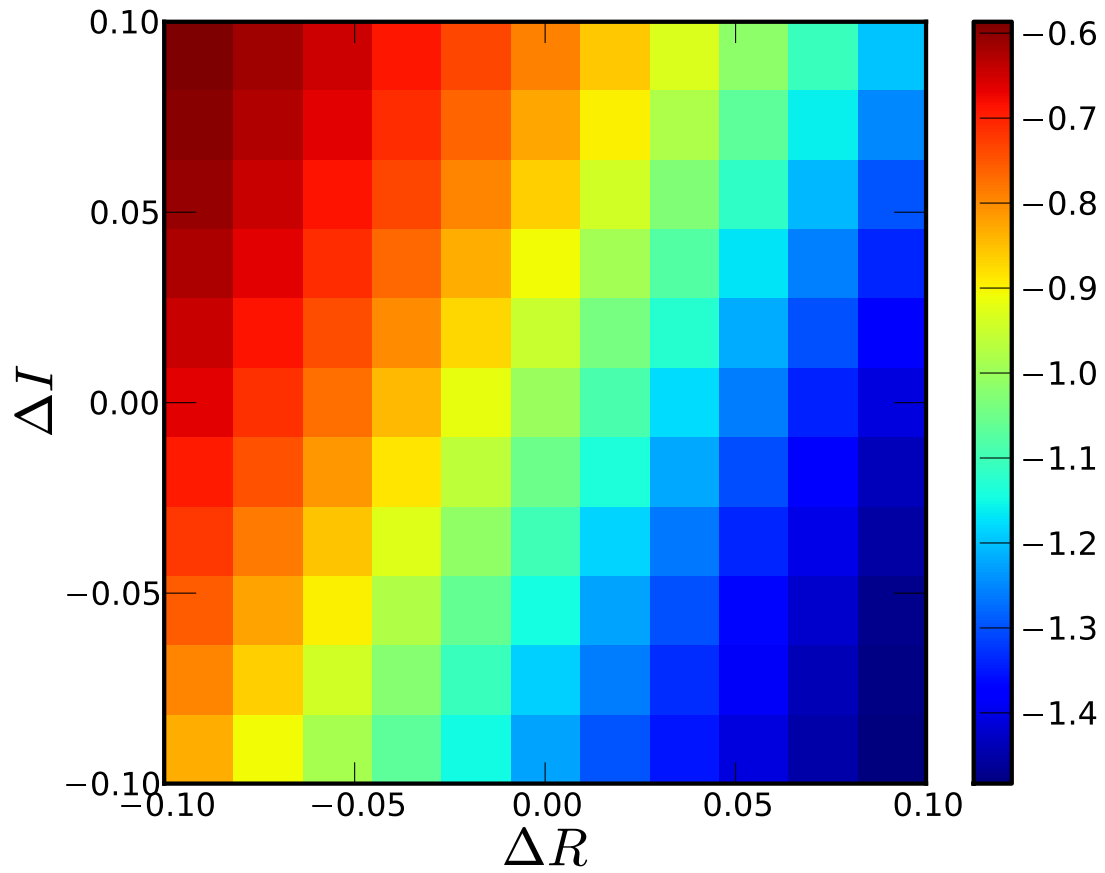
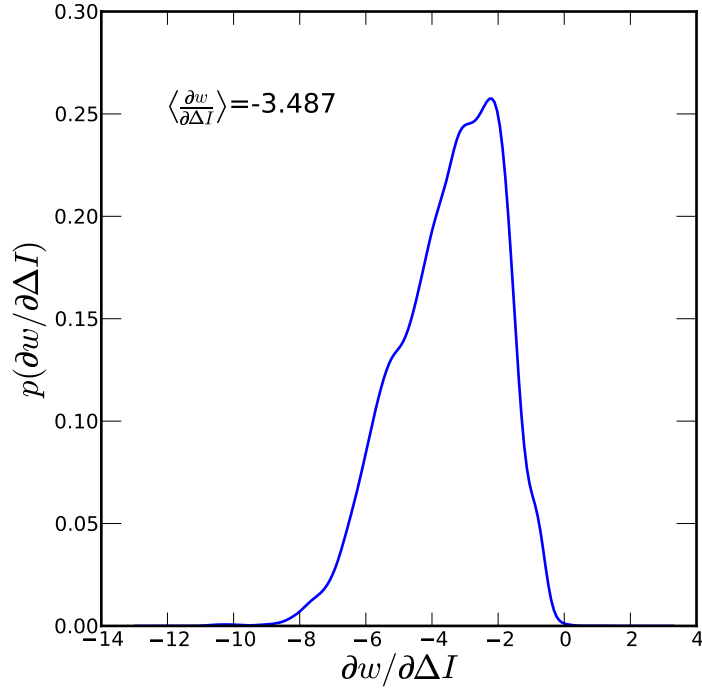


Figure 4.3 Shows the estimated value of  $w$  for zeropoint offsets in the R and I bands. The degeneracy in the diagonal direction is due to the fact that the errors on the R and I bands cancel each other (with a slope of 2) to give an accurate color estimation.

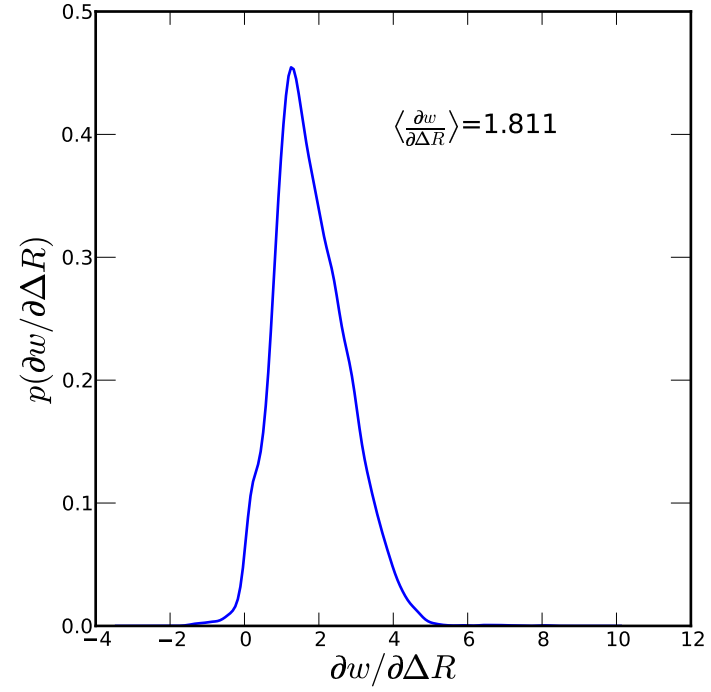
estimator. Using the probability distribution, I estimate the values of  $\langle \frac{\partial w}{\partial \Delta R} \rangle = 1.811$  and  $\langle \frac{\partial w}{\partial \Delta I} \rangle = -3.487$ . The anti-correlation of the R and I band errors are expected because estimation of supernova color depends on the rest-frame B-V color. The color is derived from the K-correction of R and I band and effectively subtract the zeropoint error of R and I. Using a known zeropoint offset error of 0.02 for both bands, I estimate the systematic error on  $w$  to be

$$\delta w = \sqrt{\left(\left\langle \frac{\partial w}{\partial \Delta R} \right\rangle\right)^2} \delta \Delta R = 0.04$$

$$\delta w = \sqrt{\left(\left\langle \frac{\partial w}{\partial \Delta I} \right\rangle\right)^2} \delta \Delta I = 0.07$$



(a) Probability distribution function of  $\partial w / \partial I_{\text{shift}}$ .



(b) Probability distribution function of  $\partial w / \partial R_{\text{shift}}$ .

Figure 4.4 Shows the probability distribution function of  $\partial w / \partial I_{\text{shift}}$  and  $\partial w / \partial R_{\text{shift}}$  estimated from 100 simulated datasets. I estimate  $\langle \partial w / \partial I_{\text{shift}} \rangle = -3.49$  and  $\langle \partial w / \partial R_{\text{shift}} \rangle = 1.811$ .

3. **Local flow:** As explained in section 4.6.3, the systematic error due to the local flow of galaxies can be estimated from the real data by applying a minimum redshift cut ( $z_{\min}$ ). I do the light curve and cosmological fitting for the data after applying the  $z_{\min}$  on the sample. Kessler et al. (2009b) found the  $w$  changes rapidly at  $z \sim 0.015$  and opted for  $z_{\min} = 0.02$ . Other authors estimated different values for  $z_{\min}$ ; for example, Conley et al. (2007) found no significant effect of local flow and Riess et al. (2007) used  $z_{\min} = 0.023$ .

The blue circles in the lower panel of figure 4.5 show the change in the estimation of  $w$ , compared to  $w$  in the last bin of  $z_{\min} = 0.029$ . The difference  $\Delta w$  is clearly visible, however compared to the error of  $w$ , the change is insignificant. I also compare our result with the result from the SDSS supernova study of Kessler et al. (2009b). Since there are many differences between this study and Kessler et al. (2009b), I explored whether the difference is due to the different datasets or different analysis. I made a new dataset that closely resembles the one from Kessler et al. (2009b) and repeated the analysis on the new dataset. This reproduced the behavior of Kessler et al. (2009b), as shown in the lower panel of figure 4.5. Because I was able to successfully reproduce the result, I conclude that the difference in the result is due to data only and the method of analysis is consistent. The upper panel of figure 4.5 shows the number of SN Ia in the corresponding bins. As can be seen from this plot, the number of SN Ia in these bins is much higher in our study. From the figure, I conclude that the local flow does not affect our result systematically.

To make a better comparison, I simulated one hundred datasets emulating our dataset. I compared how much the result from the simulation varies if we have artificial  $z_{\min}$ . Figure 4.6 shows the hundred test simulations in gray, and the red line indicates the one sigma range for those  $z_{\min}$  bins. We see that  $\Delta w$  varies in the range of -0.1 to +0.1, which is completely consistent with the error on  $w$  from our dataset. This gives further conformation that the local flow does not add any appreciable systematic error to the cosmological parameter estimation.

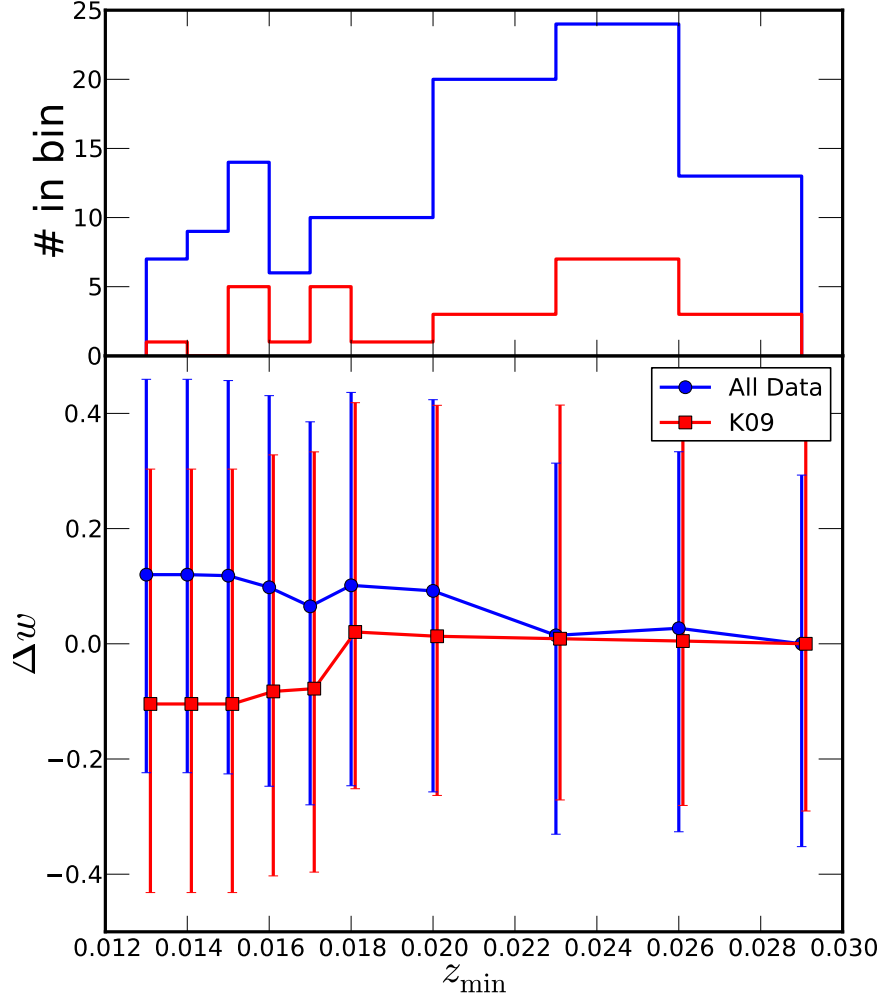


Figure 4.5 The lower panel shows the change in  $w$  compared to the choice for last bin of  $z_{\min} = 0.029$ . The blue circles are our dataset. The red square is the reproduction of the [Kessler et al. \(2009b\)](#) plot using a subset of all data that is common to their dataset. The error bars denote the error on the estimation of  $w$ . The correct reproduction of low estimate of  $w$  at  $z_{\min} < 0.018$  shows that the difference between these studies is purely data driven. The upper panel gives the number of SN Ia in each bin. The larger number of supernova in our studies (blue line compared to red one) removes the data sensitivity to local flow systematics.

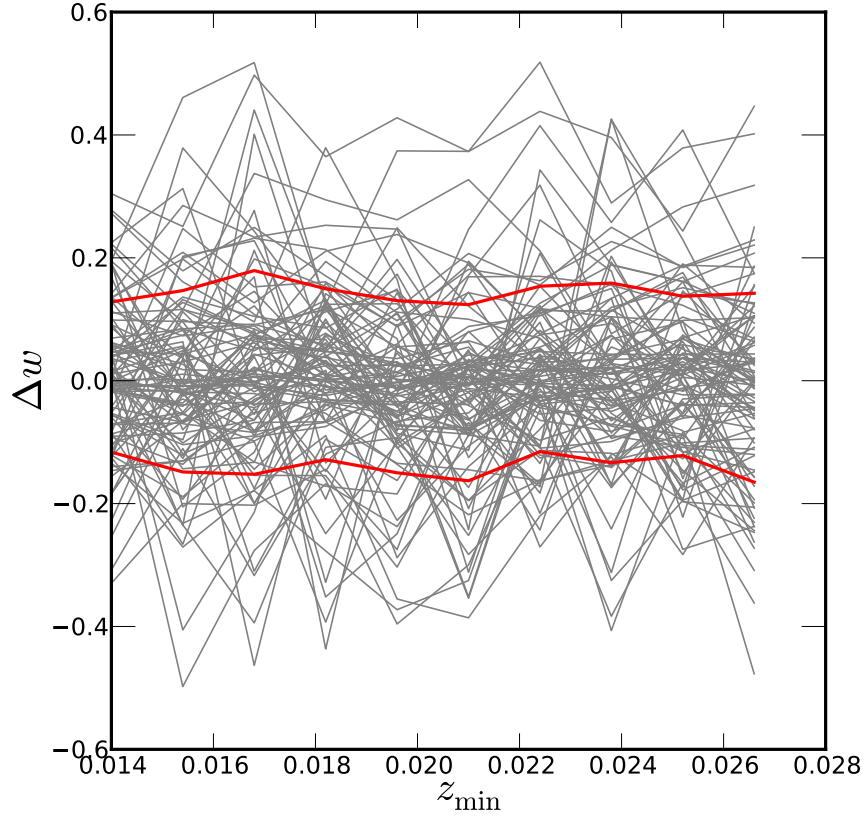


Figure 4.6 This figure estimates  $\Delta w$ , which is due to random variation. Each gray line is one of the 100 simulations of  $\Delta w$ , as a function of the minimum redshift cut. The red line is the one sigma range of all of the simulations. The range of variation of  $\Delta w$  is similar to the variation in the real dataset. This leads us to conclude that there is no appreciable local flow effect in the cosmological parameter estimation.



## 4.7 CONCLUSION AND FUTURE DIRECTION

The ESSENCE survey has produced 203 confirmed supernova Ia. The large number of supernovae reduces the measurement error of the equation of state parameter  $w$ . Much effort was spent to study the different sources of systematic error to improve upon the earlier systematic error estimation. I concentrated on the sources that could make a big contribution to the systematic errors; dust extinction, photometric zeropoint offsets, local velocity. I calculated the full distribution of systematic error on  $w$  for each source of uncertainty. The distribution checked the validity of a Gaussian approximation of the error. It also checked if the distribution was too skewed, as it could lead to an underestimation of the systematic error.

Using the analysis, I estimated the systematic error on  $w$  to be 0.135 for current SN Ia datasets. Table 4.1 shows the systematic errors of the different components on  $w$ . I also verified that there is no measurable error due to local flow. The results are going to be part of the final ESSENCE cosmology paper (in prep.). The paper will present the cosmological parameter estimation from supernovae from the ESSENCE survey and other supernova surveys. The systematic error estimation is one of most important results of the study, as well as the most complicated part of analysis.

I used the SALT II light curve fitter for this analysis. I was unable to estimate the systematic error due to use of SALT II light curve fitter compared to the use of other fitters. Other notable sources of systematic error that should be explored in future work include redshift dependence of dust, redshift dependence of the intrinsic brightness of the supernova, and use of U-band photometry for nearby versus distant supernova. We should also explore better photometric calibration because the zero point offset is a major source of uncertainty for  $w$ .

Table 4.1 Table of systematic errors on  $w$

$p$	$\frac{\delta w}{\delta p}$	$\sigma_p$	$\delta w$
Dust Extinction $\beta$	-0.132	1.0	0.13
Zeropoint R	1.811	0.02	0.04
Zeropoint I	-3.487	0.02	0.07
Total			0.15

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## APPENDIX

### ABSORPTION PIPELINE

The spectrum of an object gives a wealth of information about the object and is often essential in understanding its internal structure and properties. However all the features seen in a spectrum are not due to the object itself. The intervening material between the object and us can also make a feature in the spectrum of the object. Often these intervening material absorbs the light and hence leaving an absorption feature in the spectrum at wavelength characteristic to the wavelength of the intervening material. Since quasars are bright object and can be seen from far away, they probe a large volume of intervening space between us and them.

In the current era of astronomy, large surveys can gather spectra of thousands of objects. The number of spectra is large enough so that it is not feasible to identify features in the spectrum by manually looking at each one. Hence we have to automate the process of identifying a quasar absorption feature in the spectrum. In this chapter I present brief description of the pipeline used in SDSS and the modifications and improvements I contributed.

#### A.1 INTRODUCTION

The pipeline to identify absorber systems from the quasar spectrum has been developed by Britt Lundgren and her collaborators ([York and et al. 2012](#)). The pipeline can be described in four broad components. Figure .1 shows the schematic diagram of the absorber pipeline.

**Interface:** This part of the code is interfaced to the main SDSS spectral pipeline. It reads the fits file containing spectra of the objects and interacts with other logical parts of the code. It returns a list of absorber systems along with the lines of various species which are part of the absorption system with the properties of the lines identified. It is written using the Python programming language. The main functions of the pipeline are summarized below.

- Read the FITS file to get the spectrum.
- Pass the spectrum to the continuum fitter.
- Receive the continuum of the spectrum.
- Pass the normalized spectrum to the line finder.
- Receive the list of lines identified in the spectrum along with their properties.
- Pass the list of line for line classification.
- Receive identified absorption system along with the lines associated with them.

**Continuum Fitting:** This part of the code is responsible to find out the continuum fit for the spectrum. It take the spectrum as input and returns a continuum for the spectrum as output. Finding the continuum is a very important process to identify a line in the spectrum as it will remove all the variation cause by the intrinsic spectrum of the back-lighting object. The spectrum removes any increase of flux because of broad emission and hence facilitate finding out the narrow absorption system. This part of the code is written in C++.

**Line Finder:** This part of the code is responsible for identifying absorption lines in the normalized spectrum of the quasar. It takes the normalized spectrum as input and identifies absorption lines having large significance. It also measure various properties of absorption lines (i.e. wavelength, equivalent width, Full-width at Half max). This part of the code is written in C++.

**Line Classification:** This part of the code classify the absorption line into different elemental and ionization species using information about presence of a doublet absorption line, the line ratio, the redshift of the back-light quasar, wavelength of the absorption line. It also tries to associate identified lines of different species into one absorption system. To

identify absorption systems which have an abundance of different species of ions. This part of the code is written in Python.

## **A.2 SHORTCOMING IN USABILITY OF THE PIPELINE**

The pipeline, although algorithmically sound, suffers from problems of inefficiencies and poor portability. Some part of the pipeline was written in C++ programming language and some other parts in Python. The main interface to the pipeline is written in the Python programming language. For seamless portability the information of the spectrum should be able to pass from Python to C++ and vice versa seamlessly. That was not the case for the pipeline. The interfacing between different component of the program was achieved by writing down the intermediate state to flat files and passing the names of the flat file from Python to C++ and vice versa. This caused too many files to be made and significant reduction in speed by just reading and writing the files. This inefficiency does not pose any problem for a single spectra. However, with ever increasing number of quasars with spectra it pose a significant challenge in managing memory and also speed. Hence an improvement in the pipeline was required to be able to be useful. Below we summarize the shortcoming of the previous pipeline;

- It required very large disk space as many files had to be made for every single spectra.
- It was slow as it does too many input/output operations, which is slow.
- It was not scalable because as the number of spectrum to be processed grows the program became unusable very fast.

## **A.3 IMPROVEMENT IN PIPELINE**

I made significant improvement in usability of the pipeline. These improvements in the pipeline was imperative to be able to analyze the large amount of spectrum. The most pressing problem of the pipeline was the excessive input/output operation to overcome the

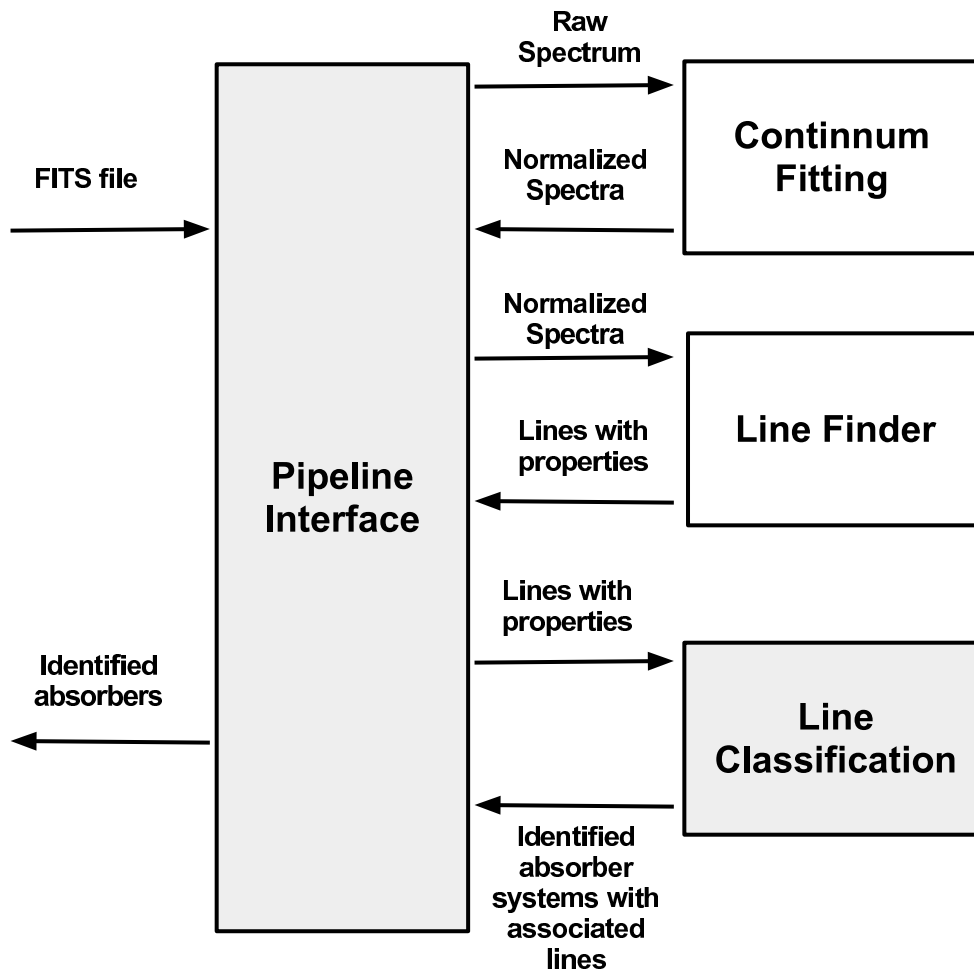


Figure .1 Schematic diagram describing the pipeline. The gray boxes indicates the part written in python. The unfilled boxes represent the code which is written in C++.

problem of interfacing between Python and C++ programming language. I overcame this by effective use of “SWIG” to generate interface Python and C++ code.

### **A.3.1 What is SWIG?**

SWIG is a program which generates interface code for a C/C++ program to be able to be used in the scripting language such as Python (and many more). It take the C/C++ declaration and use them to generate the wrapper code in C/C++. It also generate code in scripting language which defines the objects from C/C++ in the scripting language. Hence it enables the C/C++ function and objects to be accessible in scripting language. It also understand many nuances of C/C++ programming language and scripting language and tries to generate code which is compatible with such nuances, without the need for the user of SWIG to know and understand these nuances. Hence it enable fast development and portability of between diverse code and users.

### **A.3.2 Changes for input/output issues.**

As a solution to the problem we used the SWIG to make the interface code which interface with both C++ module “Continuum Fitting” and “Line Finder”. SWIG also generated a Python module which interacts with the generated C++ wrapper code. Hence once the wrapper code is generated the logical picture of different parts of the code looks as describe in figure [.2](#).

### **A.3.3 Other improvements**

I introduced some other improvements to the pipeline to improve its ability to process a large amount of spectrum without any interaction. These changes are listed below.

- Handle exception in line finding to make the code more robust against unexpected situation in data.
- Cleaned up the code by removing unused part of the code and made logic behind the code more easy to understand.

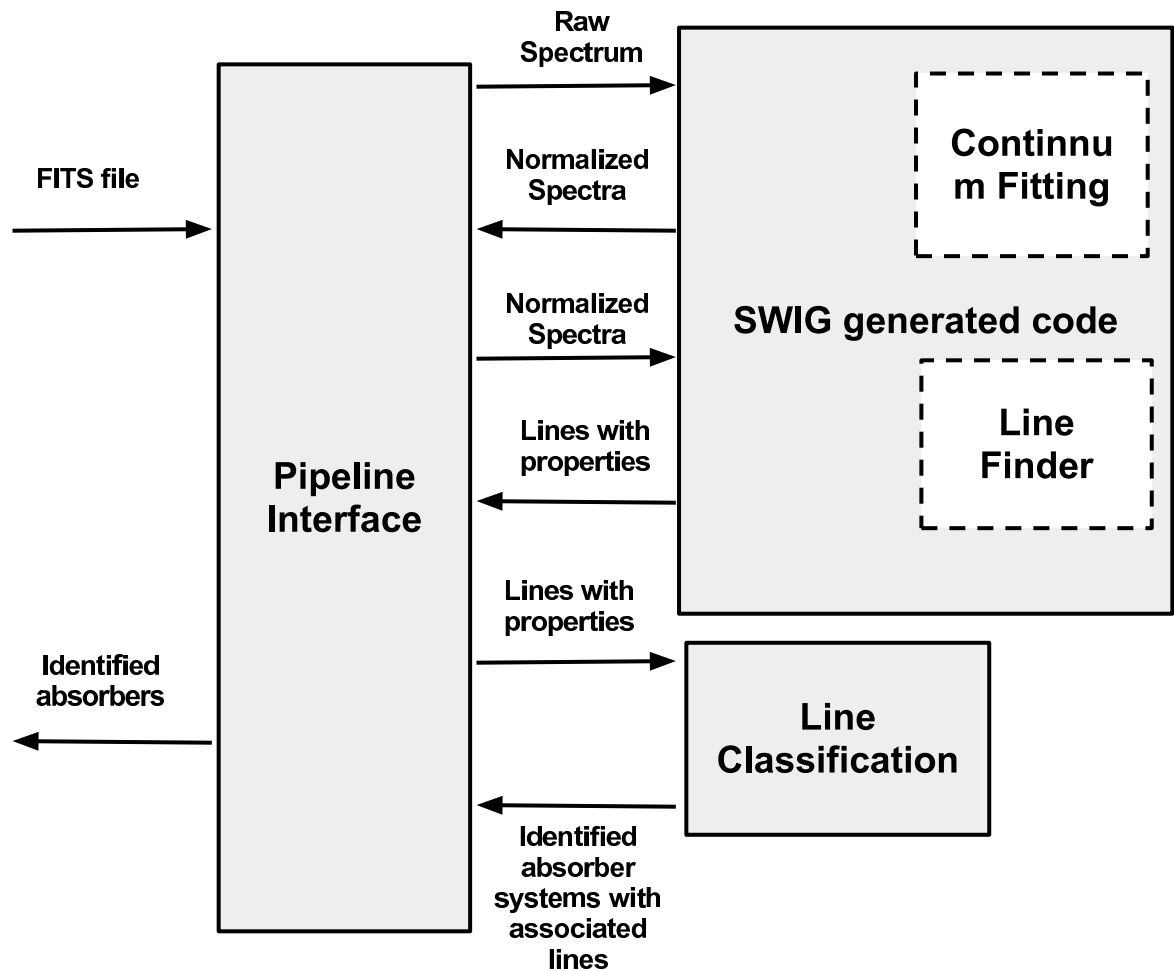


Figure .2 Schematic diagram describing the pipeline using swig. The gray boxes indicate the code written in python. Swig generated box is gray as it seems normal python code to the main interface of the program which is written in python. However in detail the generated code call the c++ compiled code transparently.



- Used FITS file to store information about identified absorber system along with line associated with it.

These changes speed up processing, allowed for automated processing of the full SDSS data set, are now use by others in the SDSS-III quasars working group.